

275°C

Polyimide (PI)



200°C

Polyethersulphone (PES)

Polyetherimide (PEI)

Polyarylate (PAR)

170°C

150°C

Polyestercarbonate (PC)

Polyethylenenaphthalate (PEN)

Polyethyleneterephthalate (PET)

# EMERGING TRANSPARENT CONDUCTING OXIDES FOR ELECTRO-OPTICAL APPLICATIONS

## CHARACTERISTICS OF EMERGING TCO MATERIALS

Material	Transmittance (%)	Resistivity ( $\times 10^{-4} \Omega \text{cm}$ )	Concentration ( $\times 10^{20} \text{ cm}^{-3}$ )	Carrier Mobility ( $\text{cm}^2/\text{V}\text{s}^{-1}$ )	Film Thickness (nm)	References
CdSn <sub>2</sub> O <sub>4</sub>	88	1.2	9.0	59.6	530	Wu, X. et al., JVSTA 15(3), 1997
CdGa <sub>2</sub> O <sub>4</sub>		83	10			Omata, T. et al., Appl. Phys Lett 62 (5) 1993
CdIn <sub>2</sub> O <sub>4</sub>	90	2.3	6.1	44.2	290	Wu, X. et al., JVSTA 15(3), 1997
CdSb <sub>2</sub> O <sub>6</sub> (Y)	90	240	1.3	1.9	170	Yanagawa, K. et al. Appl. Phys. Lett. 65(4) 1994
Cd <sub>2</sub> GeO <sub>4</sub>	98 (Internal)	1000	0.1	5		Hosono, H. et al., Appl. Phys. Lett 67(18) 1995
ITO	91	1-2	10	37	140	Heiz, b., OIC Topical Meeting, 1998

Appendix B

# EMERGING TRANSPARENT CONDUCTING OXIDES FOR ELECTRO-OPTICAL APPLICATIONS

## CHARACTERISTICS OF EMERGING TCO MATERIALS

Material	Transmittance (%)	Resistivity ( $\times 10^{-4} \Omega \text{cm}$ )	Carrier Concentration ( $\times 10^{20} \text{cm}^{-3}$ )	Mobility ( $\text{cm}^2/\text{V}\cdot\text{s}^{-1}$ )	Film Thickness (nm)	References
ZnO(Al)	90	1.4	9.9	45	150	Imaeda, K. et al. 43rd AVS Symp. 1996
ZnO(Ga)	90	2.7	13	18	230	Imaeda, K. et al. 43rd AVS Symp. 1996
ZnSnO <sub>3</sub>	80	45	1	20	310	Minami, T. et al., JvSTA 13(3) 1995
Zn <sub>2</sub> SnO <sub>4</sub>	92	570	0.058	19.0	620	Wu, X. et al., JvSTA 15(3), 1997
Zn <sub>2</sub> In <sub>2</sub> O <sub>5</sub>	95	2.9	6.0	30	400	Minami, T. et al., Thin Solid Films 290-291, 1996
Zn <sub>3</sub> In <sub>2</sub> O <sub>6</sub>	80	3.8	3.4	46	1400	Phillips, J. et al. Appl. Phys. Lett. 67(15) 1995
ITO	91	1-2	10	37	140	Heiz, b, OIC Topical Meeting. 1998

# EMERGING TRANSPARENT CONDUCTING OXIDES FOR ELECTRO-OPTICAL APPLICATIONS

## CHARACTERISTICS OF EMERGING TCO MATERIALS

Material	Transmittance (%)	Resistivity ( $\times 10^{-4} \Omega\text{cm}$ )	Carrier Concentration ( $\times 10^{20} \text{cm}^{-3}$ )	Mobility ( $\text{cm}^2/\text{V}\cdot\text{s}^{-1}$ )	Film Thickness (nm)	References
MgIn <sub>2</sub> O <sub>4</sub>	85	20	1.8	15		Minami, T. et al., Thin Solid Films 270, 1995
MgIn <sub>2</sub> O <sub>4</sub> -Zn <sub>2</sub> In <sub>2</sub> O <sub>5</sub>	82	10	3	2	400	Minami, T. et al., ICMC TF 1995
In <sub>2</sub> O <sub>3</sub> : Ga	85	5.8	5	20	400	Minami, T. et al., JVSTA 15(3) 1997
GaInO <sub>3</sub> (Sn,Ge)	90	29	4	10	1000	Phillips, J. et al., Appl. Phys. Lett. 65(1) 1994
(GaIn) <sub>2</sub> O <sub>3</sub>	90	10	3	20	100	Minami, T. et al., JVSTA 15(3) 1997
ITO	91	1-2	10	37	140	Heiz, b., OIC Topical Meeting, 1998

**SOCIETY OF VACUUM COATERS**  
**SHORT COURSE**  
**ON**  
**Deposition and Properties of ITO and**  
**Other Transparent Conductive**  
**Coatings**

**BY**  
**Clark I. Bright**  
*Delta V Technologies, Inc.*

Appendix C

## DEPOSITION AND PROPERTIES OF ITO AND OTHER TRANSPARENT CONDUCTIVE COATINGS (TCC)

### OUTLINE (PART I)

- I. FUNDAMENTALS OF CONDUCTIVITY AND THIN FILM OPTICS p. 5
- II. TCC FUNCTION AND PERFORMANCE IN APPLICATIONS p. 41
- III. MAJOR DEPOSITION METHODS FOR TCC p. 44
- IV. IMPORTANT PROCESS PARAMETER FOR TRANSPARENT CONDUCTIVE OXIDES (TCO) p. 65
- V. DEVELOPING A TCO DEPOSITION PROCESS p. 67
- VI. TCC PROCESS EXAMPLES AND ASSOCIATED COATING PROPERTIES p. 84

DEPOSITION AND PROPERTIES OF ITO AND OTHER  
TRANSPARENT CONDUCTIVE COATINGS (TCC)

OUTLINE (PART II)

- VII. STRATEGY FOR DEVELOPING A TCC TO MEET SPECIFIC APPLICATION REQUIREMENTS p.103
- VIII. APPLICATION EXAMPLES
- IX. SPECIFYING AND SELECTING COMMERCIALLY AVAILABLE TCC p.105
- X. ADVANCED TOPICS p. 111
- XI. QUESTIONS AND ANSWERS

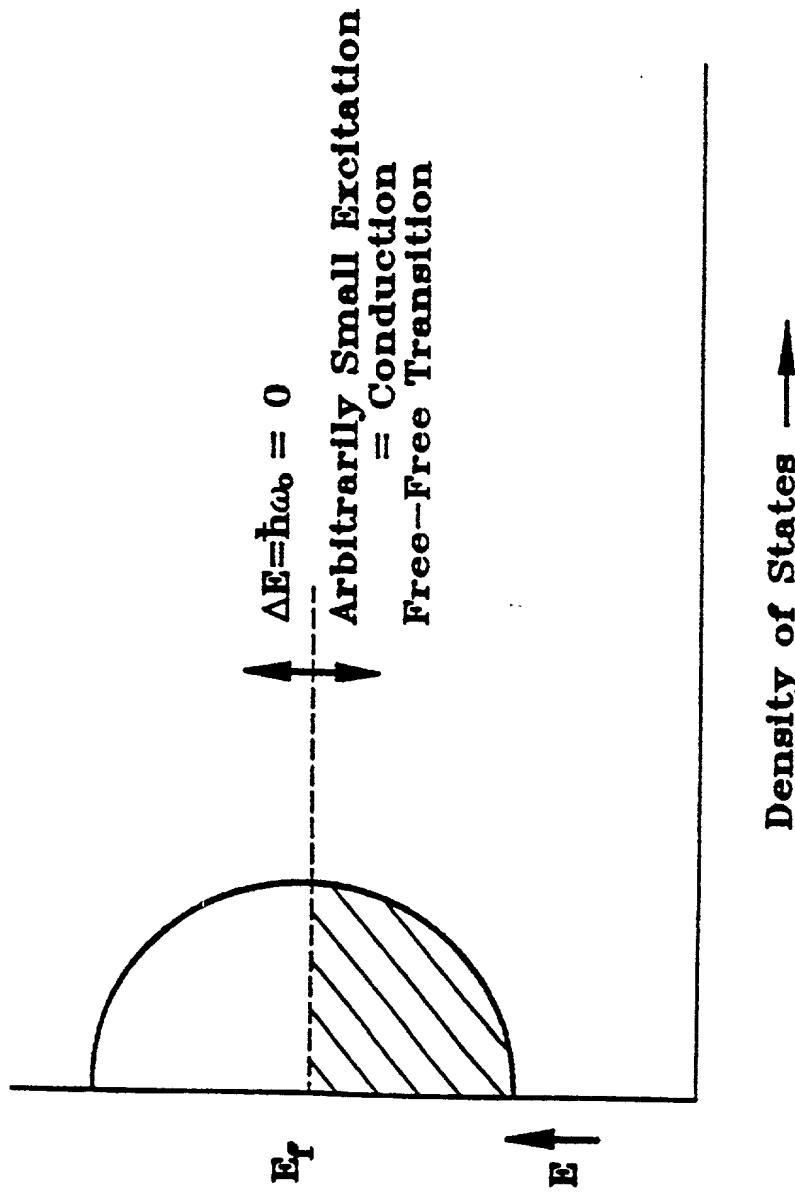
## HISTORY OF TRANSPARENT CONDUCTIVE COATINGS

- FIRST TRANSPARENT CONDUCTIVE COATING (TCC) WAS CADMIUM OXIDE USED IN PHOTOVOLTAIC CELLS IN 1907
- IN THE 1940's TIN OXIDE WAS DEPOSITED ON GLASS BY PYROLYSIS AND CHEMICAL VAPOR DEPOSITION
- IN THE 1950's THIN METALS, e.g. GOLD, WERE VACUUM EVAPORATED ON GLASS AND PLASTICS
- IN THE 1970's INDIUM OXIDE AND TIN DOPED INDIUM OXIDE (ITO) WERE MADE BY EVAPORATION AND DIODE SPUTTERING
- IN THE 1980's MAGNETRON SPUTTERING MADE IT POSSIBLE TO DEPOSIT ITO ON GLASS AND PLASTICS AT LOW TEMPERATURES WITH GOOD PERFORMANCE
- TODAY MAJOR TCC USED IN DISPLAYS AND OTHER APPLICATIONS IS ITO

# PHYSICS FUNDAMENTALS OF TRANSPARENT CONDUCTIVE COATINGS

## METAL BAND STRUCTURE

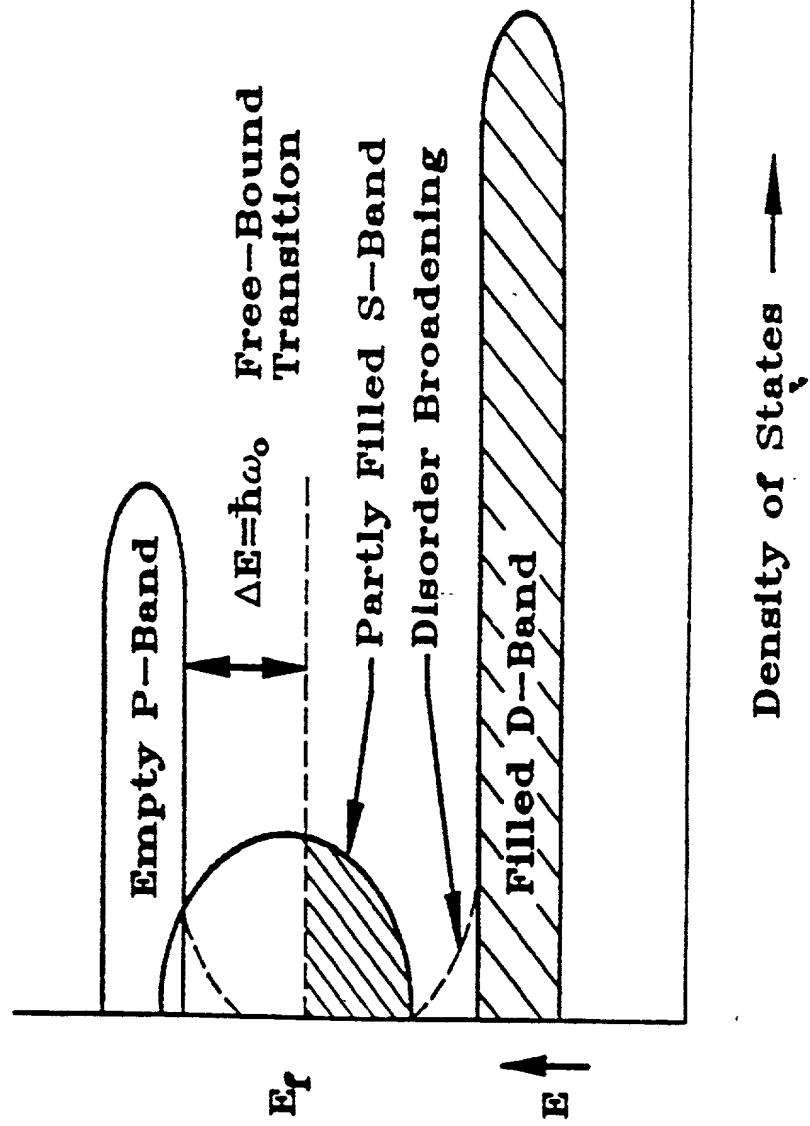
### S-BAND FREE ELECTRONS



# PHYSICS FUNDAMENTALS OF TRANSPARENT CONDUCTIVE COATINGS

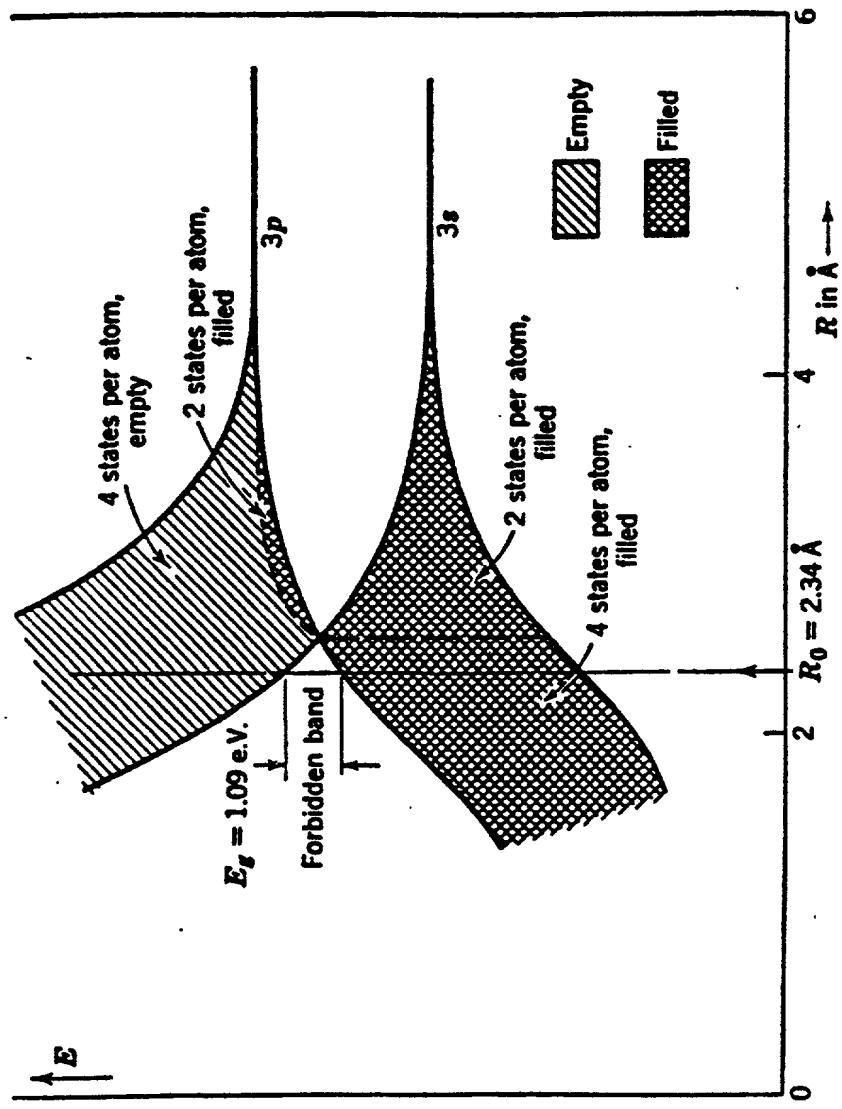
## METAL BAND STRUCTURE

### REAL S-BAND METAL



# PHYSICS FUNDAMENTALS OF TRANSPARENT CONDUCTIVE COATINGS

## SEMICONDUCTOR BAND STRUCTURE

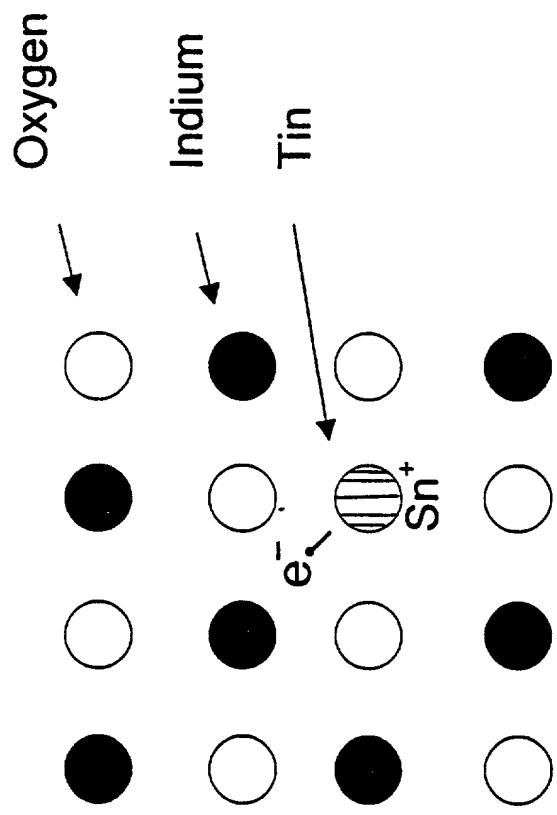


Energy Bands of Silicon as a Function of Nearest-Neighbor Distance ( $R$ )

(From R. L. Sproull, Modern Physics, Wiley, 1956)

# PHYSICS FUNDAMENTALS OF TRANSPARENT CONDUCTIVE COATINGS

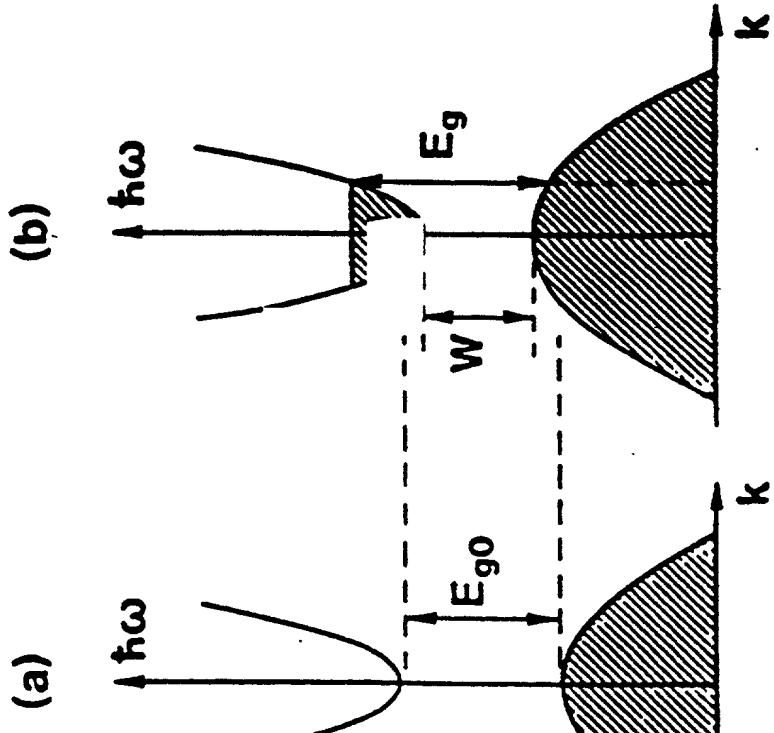
## CRYSTAL STRUCTURE



**Simplified Crystal Structure and Doping Model for Indium Tin Oxide**  
(C.G. Granqvist, Spectrally Selective Surfaces for Heating and Cooling Applications, TT 1 SPIE, 1989)

# PHYSICS FUNDAMENTALS OF TRANSPARENT CONDUCTIVE COATINGS

## BAND STRUCTURE



Assumed Band Structure for Undoped (a) and Tin Doped (b) Indium Oxide  
Shaded Areas Indicate Occupied States  
(C. G. Granqvist, Selective Surfaces for Heating and Cooling Applications, TT 1, SPIE, 1989)

# **PHYSICS FUNDAMENTALS OF TRANSPARENT CONDUCTIVE COATINGS**

## **CONDUCTIVITY**

- METALS:  
 $\sigma(\omega) = j\omega\epsilon(\omega)$   
AND FOR DC ( $\omega = 0$ )  $\sigma = N e \mu = N \frac{e^2 \tau}{m} = \omega_p^2 \tau$
- WHERE  
N = NUMBER DENSITY OF ELECTRONS  
e = ELECTRONIC CHARGE  
 $\mu$  = ELECTRON MOBILITY  
 $\tau$  = SCATTERING TIME  
m = ELECTRON MASS  
 $\omega_p$  = PLASMA FREQUENCY  
 $\omega$  = ANGULAR FREQUENCY OF RADIATION

- SEMICONDUCTORS:  
THE SAME FUNCTIONAL RELATIONS ARE DERIVED FOR BOTH ELECTRONS AND HOLES. TCO ARE HIGHLY DEGENERATE n-TYPE SEMICONDUCTORS SO EXPRESSION FOR  $\sigma$  IS THE SAME AS FOR METALS.

## PHYSICS FUNDAMENTALS OF TRANSPARENT CONDUCTIVE COATINGS

### CONDUCTIVITY

- CONDUCTIVITY OF A METAL DEPENDS ONLY ON THE NUMBER (DENSITY) OF ELECTRONS AND THEIR MOBILITY (SCATTERING TIME)
- FOR A SEMICONDUCTOR, THE CONDUCTION ELECTRONS ARE CREATED BY DOPING OR BY LACK OF STOICHIOMETRY
- FOR A TRANSPARENT CONDUCTING OXIDE (TCO), ITO et al, THE CONDUCTION ELECTRONS ARE CREATED PRIMARILY BY OXYGEN DEFICIENCIES (VACANCIES)
- THESE VACANCIES ARE CHARGE DEFECTS IN THE TCO LATTICE WHICH SCATTER ELECTRONS
- ELECTRON MOBILITY OR SCATTERING TIME DEPENDS ON THE DOPING LEVEL AS WELL AS THE TCO CRYSTALLOGRAPHIC ORDER

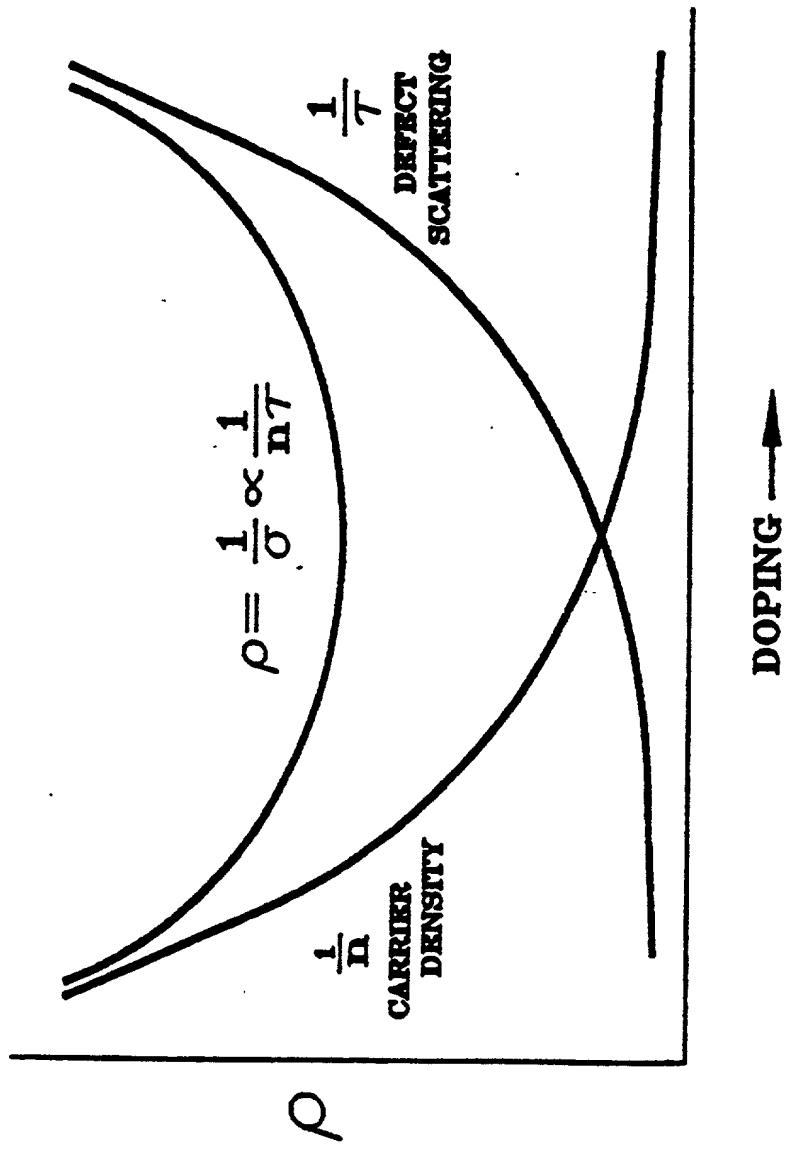
## PHYSICS FUNDAMENTALS OF TRANSPARENT CONDUCTIVE COATINGS

### CONDUCTIVITY

- FOR A GIVEN TCO DEPOSITION PROCESS THERE IS A RESISTIVITY MINIMUM
- AT LOW DOPING LEVELS THE RESISTIVITY IS INCREASED BY LACK OF CONDUCTION ELECTRONS
- AT HIGH DOPING LEVELS THE RESISTIVITY IS INCREASED BY ELECTRON SCATTERING FROM OXYGEN VACANCIES
- THE MINIMUM RESISTIVITY OCCURS WHEN SCATTERING CAUSED BY DOPING IS COMPARABLE TO SCATTERING FROM ALL OTHER DEFECTS

## PHYSICS FUNDAMENTALS OF TRANSPARENT CONDUCTIVE COATINGS

### RESISTIVITY vs DOPING



ORIGIN OF RESISTIVITY WELL

## CARRIER ABSORPTION

- THE FREE CARRIERS NEEDED FOR CONDUCTION WILL ABSORB INCIDENT ELECTROMAGNETIC (EM) RADIATION
  - ABSORPTION COEFFICIENT ( $\alpha$ ) VARIES WITH WAVELENGTH
- $$\alpha = \frac{4 \pi k}{\lambda} \quad \text{WHERE } k \text{ IS THE EXTINCTION COEFFICIENT}$$
- $$\text{AND } \lambda \text{ IS THE WAVELENGTH}$$
- METALS AND SEMICONDUCTOR HAVE CHARACTERISTIC SPECTRAL OPTICAL PROPERTIES

## PHYSICS FUNDAMENTALS OF TRANSPARENT CONDUCTIVE COATINGS

### DRUDE THEORY

- THE DIELECTRIC FUNCTION FOR CONDUCTION (FREE) ELECTRONS:

$$\epsilon(\omega) = \epsilon_1 - i\epsilon_2 = n^2 \text{ AND } n = n - ik \text{ THEN } \epsilon_1 = n^2 - k^2 \text{ AND } \epsilon_2 = 2nk$$

$$\text{AND } \epsilon_1 = 0 \text{ WHEN } \omega = \omega_p \text{ AND } \omega_p^2 = \frac{Ne^2}{\epsilon_0 m}$$

WHERE  $N$  = NUMBER DENSITY OF ELECTRONS

$e$  = ELECTRONIC CHARGE

$\tau$  = SCATTERING TIME

$m$  = ELECTRON MASS

$\omega_p$  = PLASMA FREQUENCY

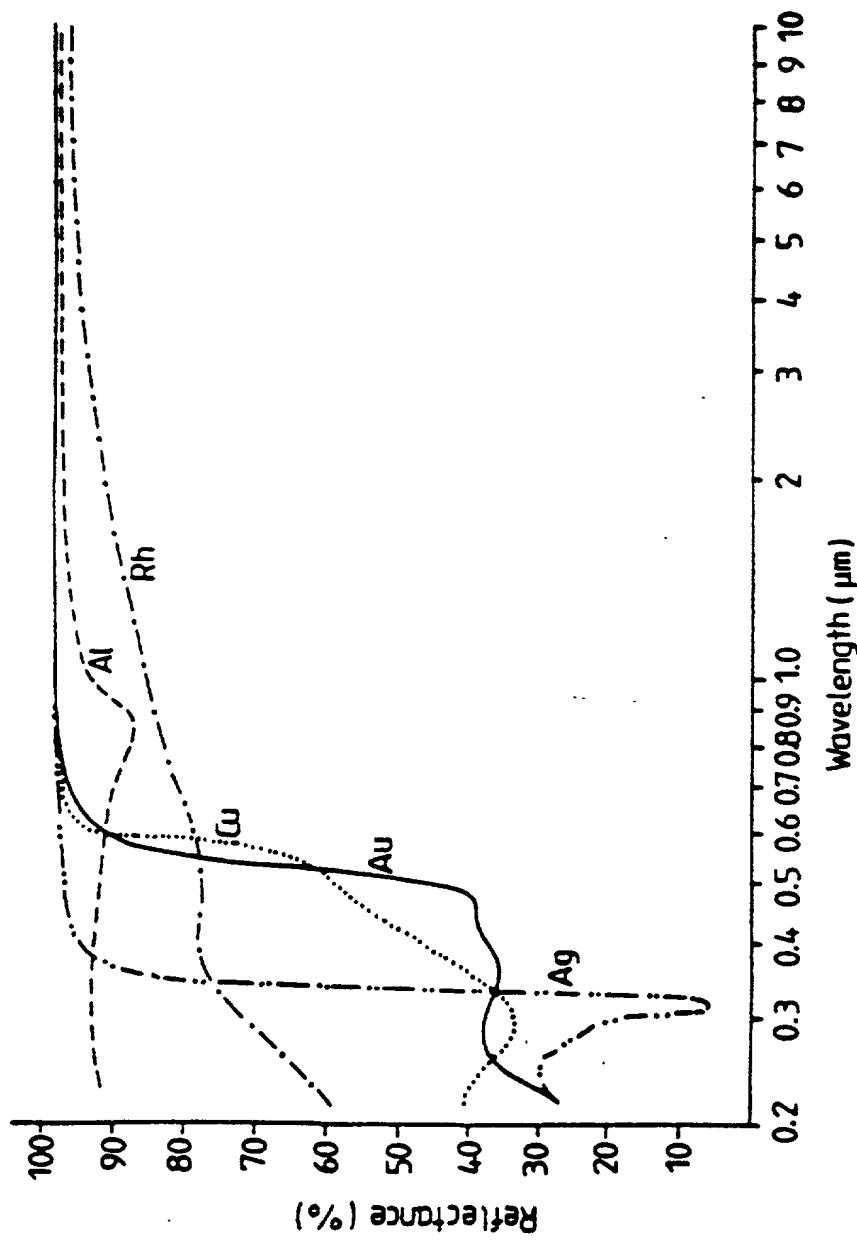
$\omega$  = ANGULAR FREQUENCY OF RADIATION

- METAL NITRIDES:

$$\epsilon(\omega) = \epsilon_1(\infty) - (\omega_p^2 / \omega^2 + i\omega/\tau) \text{ AND } \omega_p^2 = \frac{N e^2}{\epsilon_0 m^*}$$

# PHYSICS FUNDAMENTALS OF TRANSPARENT CONDUCTIVE COATINGS

## OPTICS OF METALLIC THIN FILMS

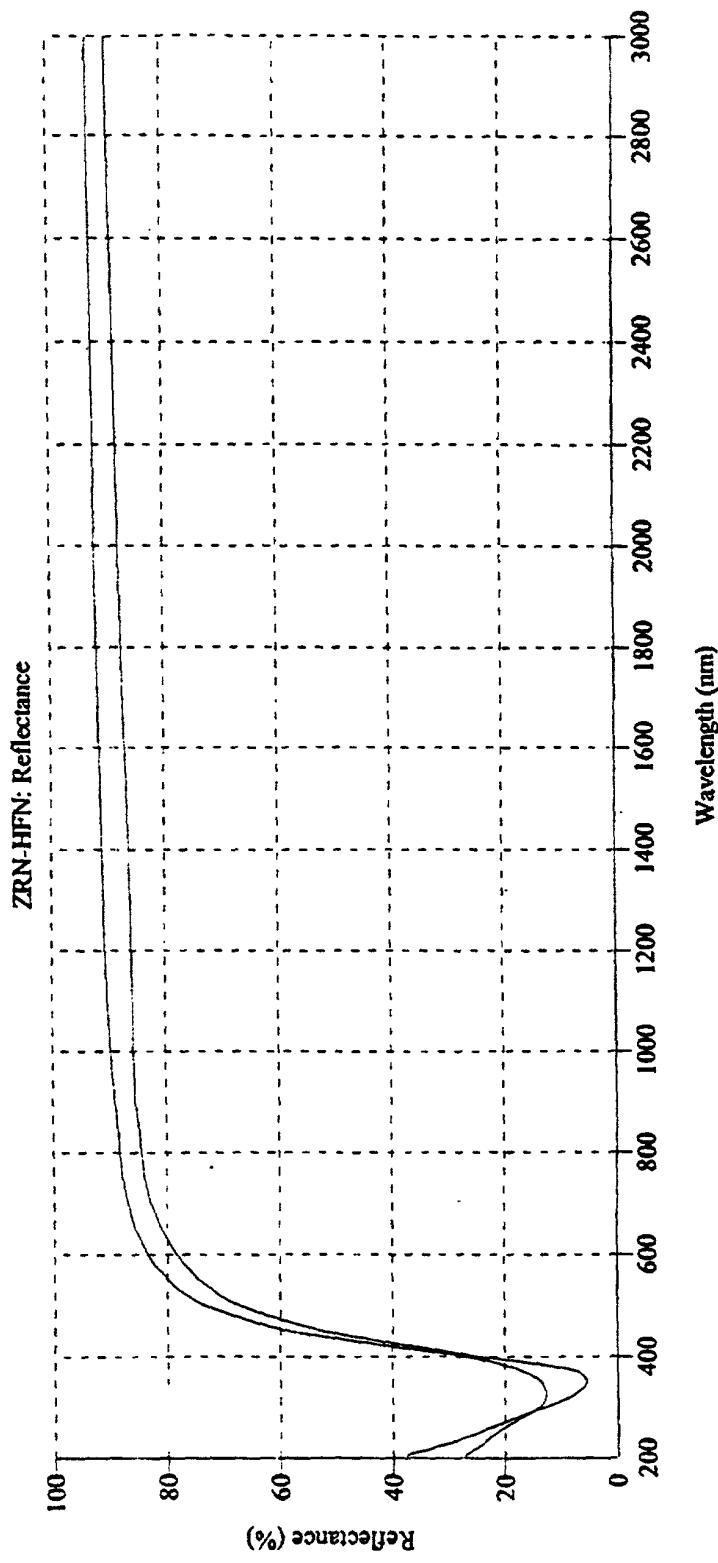


Change in Reflectance at Plasma Wavelength for Simple Metals (Au, Ag, Cu)

(From G. Hass, J. Opt. Soc. Am. 45, 945-52, 1955)

# PHYSICS FUNDAMENTALS OF TRANSPARENT CONDUCTIVE COATINGS

## OPTICS OF METALLIC NITRIDE THIN FILMS

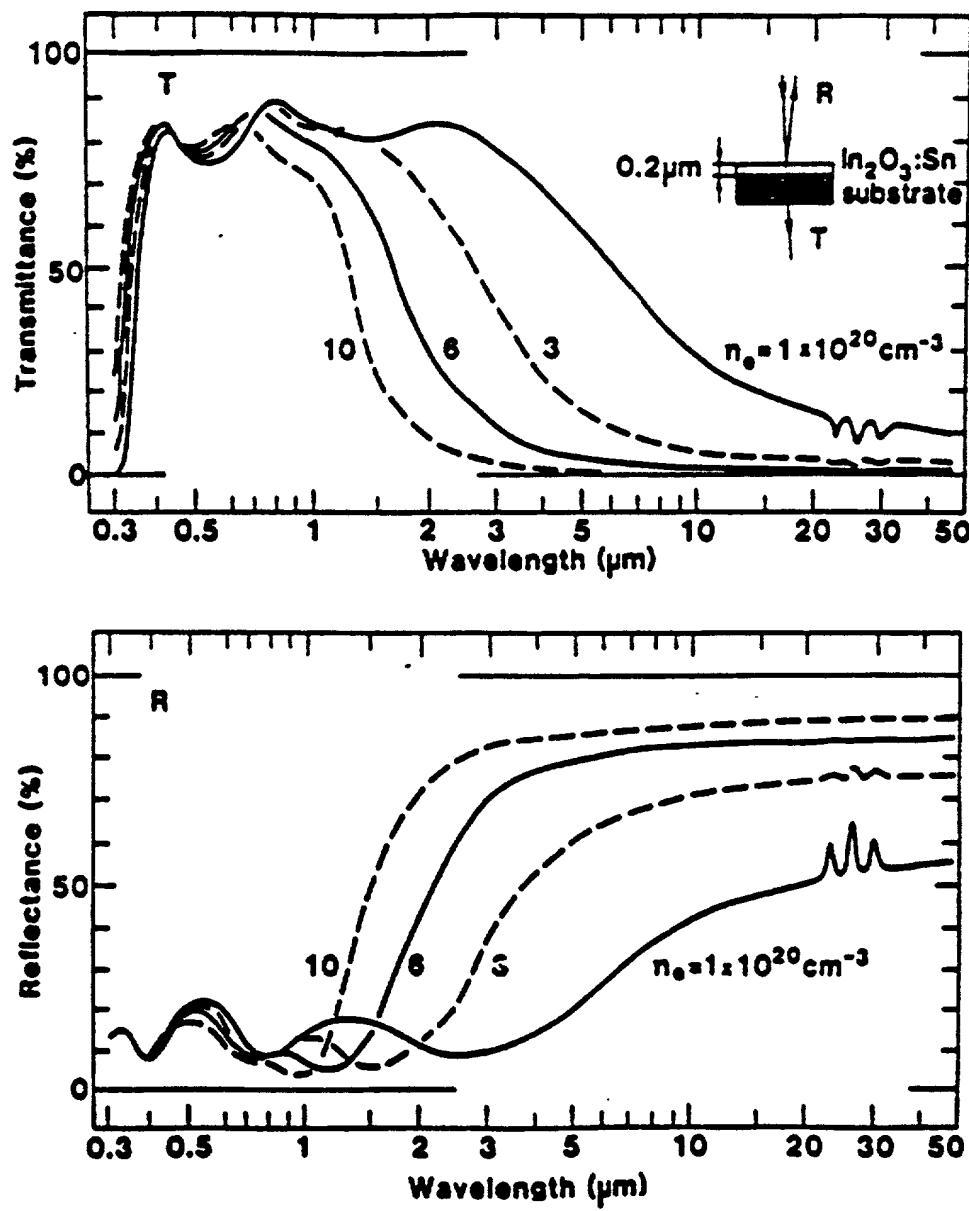


Change in Reflectance at Plasma Wavelength for HfN, ZrN  
HfN – lower trace, ZrN – upper trace

(Calculated from optical constants in E.D. Palik, Ed. Handbook of Optical Constants of Solids III)

# PHYSICS FUNDAMENTALS OF TRANSPARENT CONDUCTIVE COATINGS

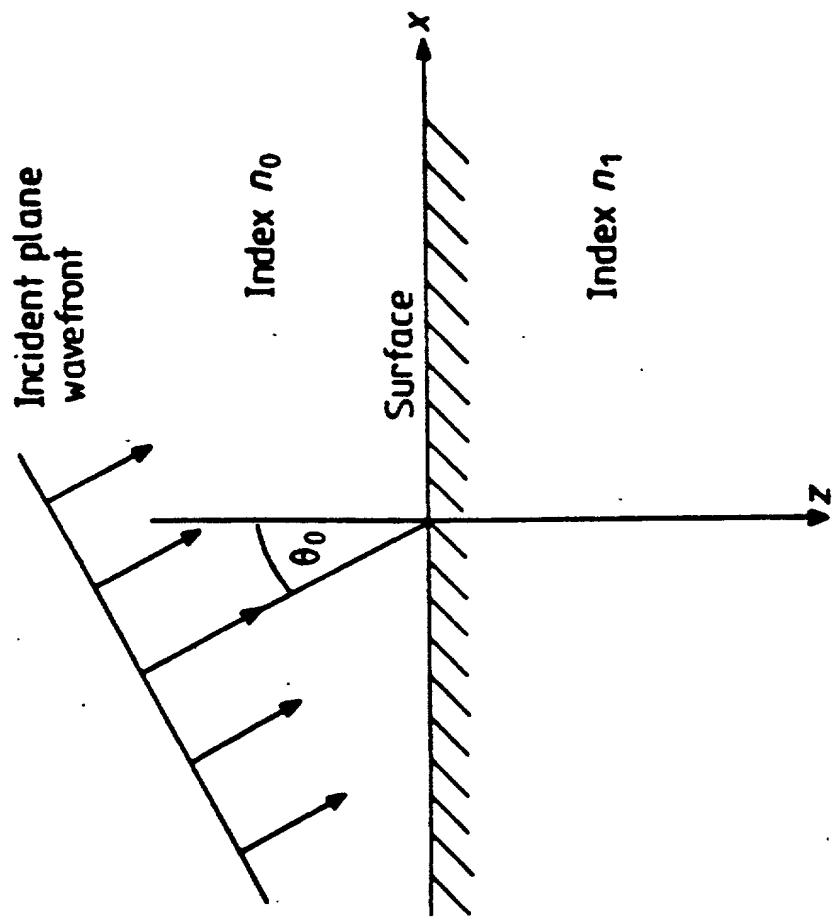
## CONDUCTIVITY



Spectral Properties of ITO as a Function of Carrier Density ( $n_e$ )  
(From, J. App. Opt. 24, 12 15june 1985)

# PHYSICS FUNDAMENTALS OF TRANSPARENT CONDUCTIVE COATINGS

## THIN FILM OPTICS



Plane Wave Incident on a Single Surface  
(From Thin Film Optical Filters, H. A. Macleod, Macmillan, 1968)

## PHYSICS FUNDAMENTALS OF TRANSPARENT CONDUCTIVE COATINGS

### THIN FILM OPTICS

#### REFLECTANCE OF SINGLE SURFACE

$$R = \left\{ \frac{n_{\text{MEDIUM}} - n_{\text{FILM}}}{n_{\text{MEDIUM}} + n_{\text{FILM}}} \right\}^2$$

EX: FOR  $n_{\text{FILM}} = 2.0$  and  $n_{\text{MEDIUM}} = 1.0$  (AIR)

$$R = \left\{ \frac{1 - 2}{1 + 2} \right\}^2 = 0.11111 = 11.1\% \text{ (PER SURFACE)}$$

EX: FOR  $n_{\text{FILM}} = 1.51$  and  $n_{\text{MEDIUM}} = 1.0$

$$R = \left\{ \frac{1 - 1.51}{1 + 1.51} \right\}^2 = 0.0413 = 4.1\% \text{ (PER SURFACE)}$$

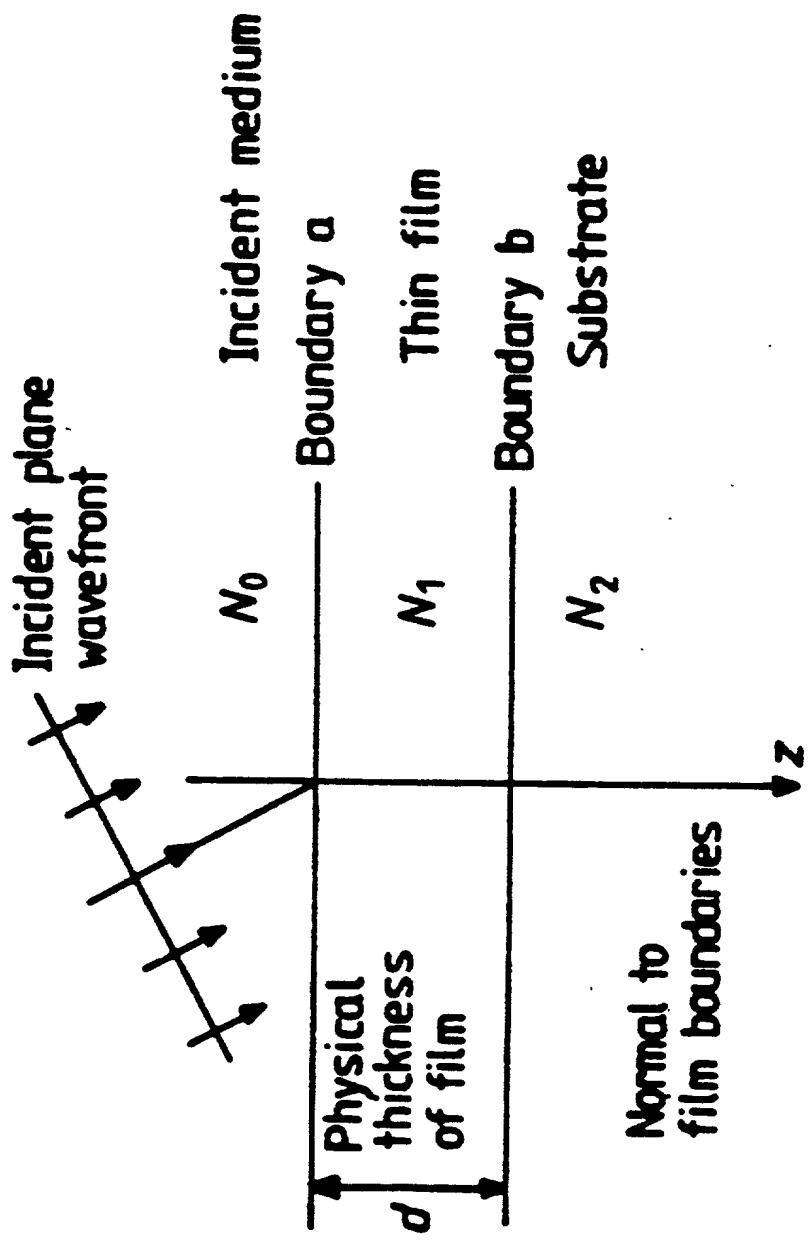
EX: FOR  $n_{\text{FILM}} = 2.0$  and  $n_{\text{SUB}} = 1.51$

$$R = \left\{ \frac{n_{\text{SUB}} - n_{\text{FILM}}}{n_{\text{SUB}} + n_{\text{FILM}}} \right\}^2 = \left\{ \frac{1.51 - 2.0}{1.51 + 2.0} \right\}^2 = 0.0195 = 1.95\%$$

Q.

# PHYSICS FUNDAMENTALS OF TRANSPARENT CONDUCTIVE COATINGS

## THIN FILM OPTICS



Plane Wave Incident on a Thin Film  
(From Thin Film Optical Filters, H. A. Macleod, Macmillan, 1968)

## **PHYSICS FUNDAMENTALS OF TRANSPARENT CONDUCTIVE COATINGS**

### **THIN FILMS OPTICS**

- OPTICAL THICKNESS IS THE PRODUCT OF INDEX OF REFRACTIONS AND PHYSICAL THICKNESS =  $n \times d$  (WAVES)

- QUARTERWAVE OPTICAL THICKNESS =  $n \times d = \frac{\lambda}{4}$

EX: FOR  $n = 2$  AND  $d = 100$  NM

$$\lambda_{1/4} = 4 \text{ nd} = 800 \text{ NM}$$

- HALF WAVE OPTICAL THICKNESS =  $n \times d = \frac{\lambda}{2}$

EX: FOR  $n = 2$  AND  $d = 100$  NM

$$\lambda_{1/2} = 2 \text{ nd} = 400 \text{ NM}$$

## PHYSICS FUNDAMENTALS OF TRANSPARENT CONDUCTIVE COATINGS

### THIN FILM OPTICS

- SINGLE LAYER ON A SUBSTRATE

$$R_M = \left\{ \frac{n_{\text{FILM}}^2 - n_0 n_{\text{SUB}}}{n_{\text{FILM}}^2 + n_0 n_{\text{SUB}}} \right\}^2 \quad \text{WHERE } n_0 \text{ IS THE INCIDENT MEDIUM INDEX}$$

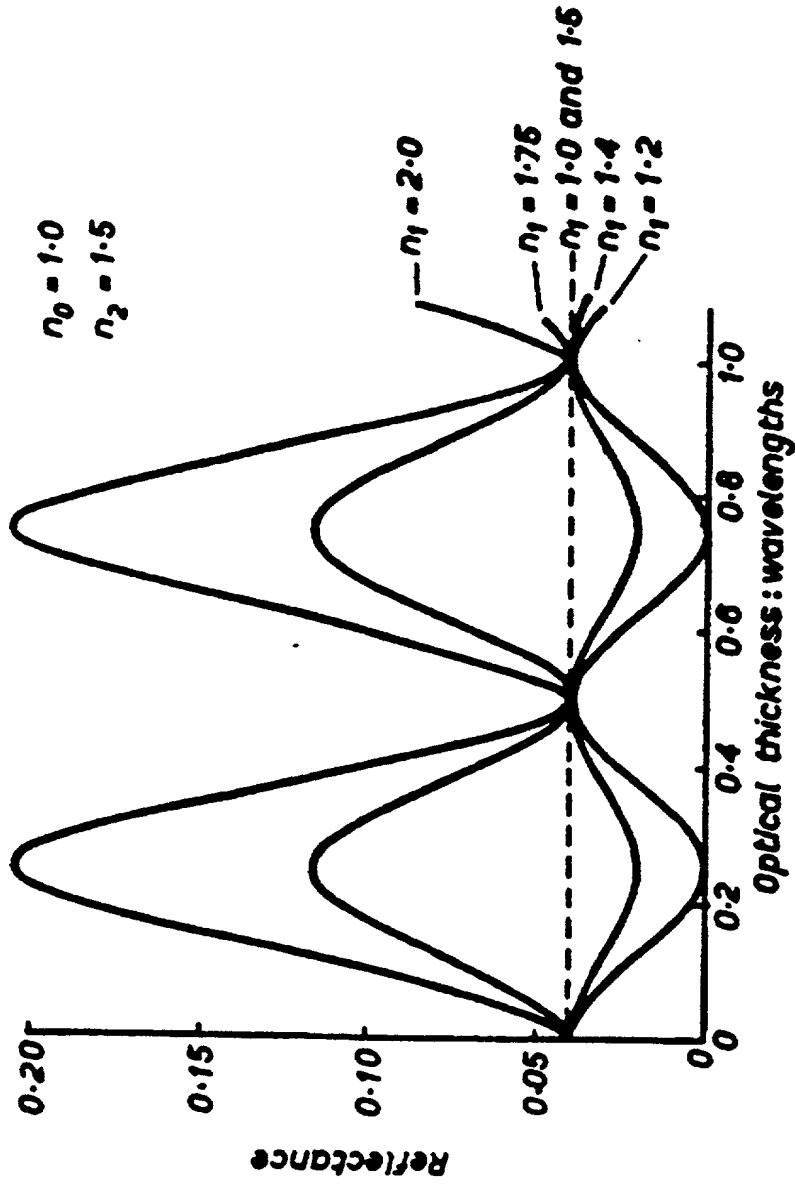
$R_M$  IS EITHER A MAXIMUM OR A MINIMUM IF THE OPTICAL THICKNESS IS AN ODD MULTIPLE OF A QUARTERWAVE, e.g.  $\frac{\lambda}{4}, \frac{3\lambda}{4}, \frac{5\lambda}{4}$ , etc

EX: FOR  $n_{\text{FILM}} = 2.0$ ,  $n_{\text{SUB}} = 1.51$  AND  $n_0 = 1.0$

$$R_M = \left\{ \frac{4 - 1.51}{4 + 1.51} \right\}^2 = 0.2042 = 20.42\%$$

# PHYSICS FUNDAMENTALS OF TRANSPARENT CONDUCTIVE COATINGS

## THIN FILM OPTICS



Variation of reflectance (at air side) with thickness for films of various refractive indices on a substrate of index 1.5

(From O.S. Heavens, Optical Properties of Thin Solid Films, Dover, 1985)

# **PHYSICS FUNDAMENTALS OF TRANSPARENT CONDUCTIVE COATINGS**

## THIN FILMS

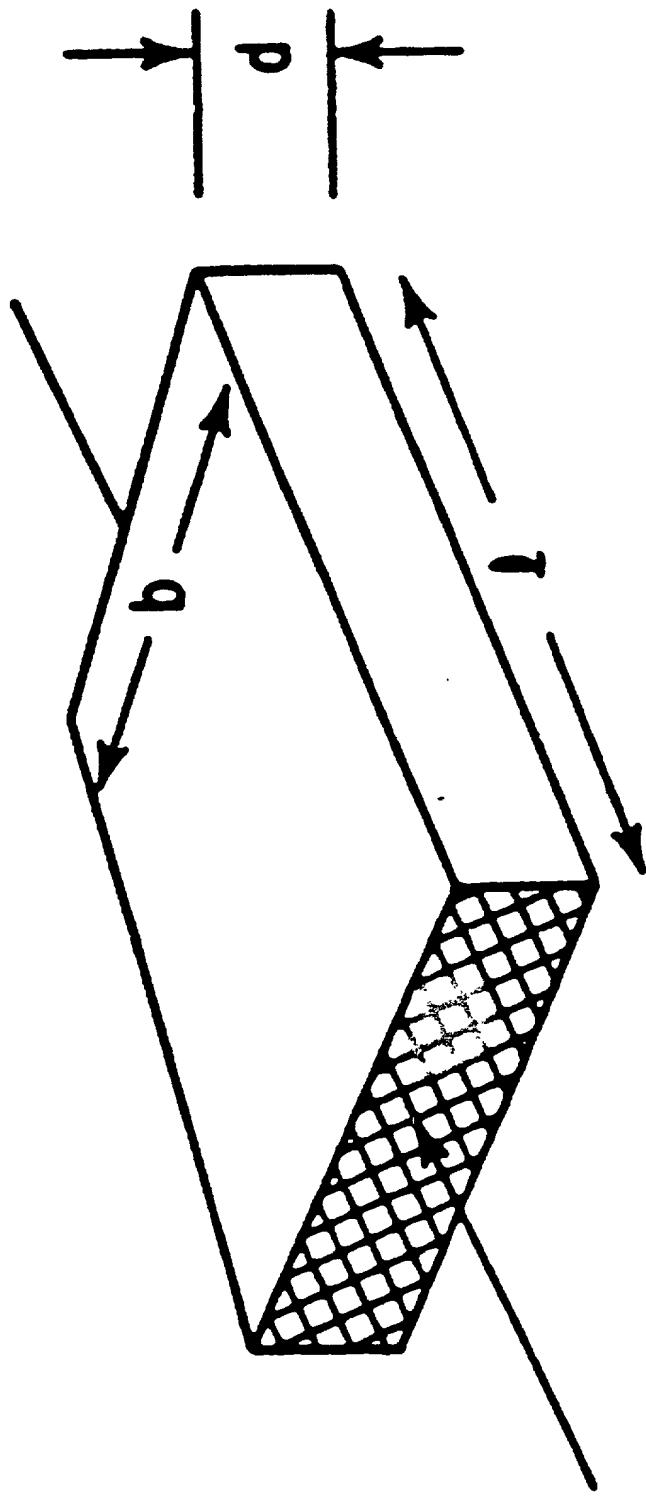
### SURFACE RESISTIVITY

- CONDUCTIVITY IS RECIPROCAL OF VOLUME RESISTIVITY ( $\rho$ )

$$\rho = \frac{1}{\sigma} \text{ OHM - CM}$$

- HOWEVER, VOLUME RESISTIVITY CAN BE MISLEADING BECAUSE THIN FILMS ARE OFTEN INHOMOGENEOUS, CONTAIN DEFECTS, CAN EXHIBIT SURFACE SCATTERING, AND FILM THICKNESS IS DIFFICULT TO MEASURE ACCURATELY
- THEREFORE SURFACE (SHEET) RESISTIVITY ( $r$ ) IS USED

## PHYSICS FUNDAMENTALS OF TRANSPARENT CONDUCTIVE COATINGS



### SURFACE RESISTIVITY

$$R = \frac{p \times l}{b \times d} \text{ OHMS}$$
$$r = \frac{R \times b}{l} \text{ IN UNITS CALLED OHMS/SQUARE}$$

$$R = \frac{p \times l}{d} \text{ OHMS}$$

BECAUSE WHEN  $l = b$ , i.e., ON A SQUARE AREA, THE SURFACE RESISTIVITY EQUALS THE MEASURED RESISTANCE,  $r = R$  (OHMS)

## PHYSICS FUNDAMENTALS OF TRANSPARENT CONDUCTIVE COATINGS

### THIN FILMS

#### SURFACE RESISTIVITY

- NOTE THAT THE MEASURED VALUE OF  $r$  IS INDEPENDENT OF THE SIZE OF THE SQUARE (AREA)
- IT IS ONLY DEPENDENT ON THE GEOMETRIC RATIO OF WIDTH TO LENGTH ( $b/l$ )
- THUS A SQUARE INCH OR A SQUARE METER OF COATING WILL HAVE THE SAME RESISTANCE

## PHYSICS FUNDAMENTALS OF TRANSPARENT CONDUCTIVE COATINGS

### THIN FILMS

#### SURFACE RESISTIVITY

- COMPARE THE THEORETICAL COATING THICKNESSES (BULK MATERIAL) OF TWO 10 OHMS/SQUARE THIN FILMS:

FOR	$\frac{\text{ITO}}{\rho = 2 \times 10^{-4} \text{ OHM-CM}}$	$\frac{\text{GOLD}}{\rho = 2.4 \times 10^{-6} \text{ OHM-CM}}$
	$r = \frac{\rho}{d} = 10 \text{ OHMS/SQUARE}$	$r = \frac{\rho}{d} = 10 \text{ OHMS/SQUARE}$
	$d = \frac{\rho}{r} = 2 \times 10^{-5} \text{ CM}$	$d = \frac{\rho}{r} = 2.4 \times 10^{-7} \text{ CM}$
	$d = 200 \text{ NM}$	$d = 2.4 \text{ NM}$

- THUS FOR THE SAME OHMS/SQUARE, SEMICONDUCTOR TCC ~ 100X THICKER THAN METALLIC TCC

# PHYSICS FUNDAMENTALS OF TRANSPARENT CONDUCTIVE COATINGS

## OPTICS

- SPECTRAL VALUES

TRANSMITTANCE IS  $T(\lambda)$ , REFLECTANCE  $R(\lambda)$ , ABSORPTANCE  $A(\lambda)$

$$T(\lambda) + R(\lambda) + A(\lambda) = 1$$

- INTEGRATED VALUES:

$$\text{AVERAGE - e.g. T AVERAGE} = \frac{\int T(\lambda) d\lambda}{M d\lambda}$$

WHERE M IS NUMBER OF WAVELENGTHS (INTERNAL)

$$\text{EYE WEIGHTED - LUMINOUS T} = \frac{\int T(\lambda) K(\lambda) P(\lambda) d\lambda}{P(\lambda) K(\lambda) d\lambda}$$

$$\lambda = 380\text{NM}$$

$$\lambda = 400\text{NM}$$

$$\lambda = 780\text{NM}$$

$$\lambda = 700\text{NM}$$

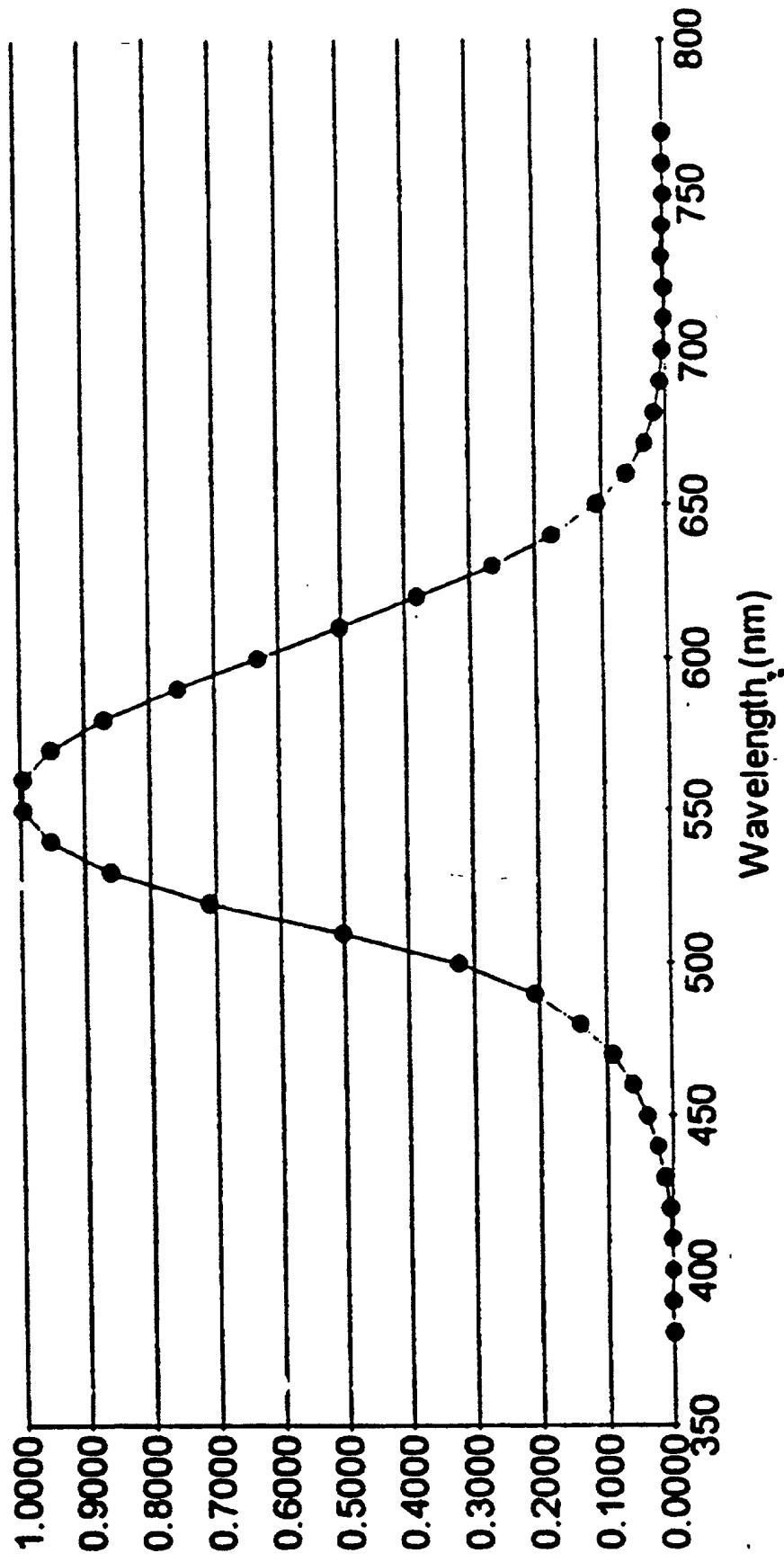
$$\int \frac{T(\lambda) d\lambda}{M d\lambda} = \sum \frac{T(\lambda) \Delta\lambda}{M \Delta\lambda}$$

WHERE  $P(\lambda)$  IS AVERAGE DAYLIGHT AND  $K(\lambda)$  IS RELATIVE SENSITIVITY OF PHOTOPIC ADAPTED EYE

"VISIBLE" - NOT DEFINED GENERALLY, OFTEN MEANS LUMINOUS

## PHYSICS FUNDAMENTALS OF TRANSPARENT CONDUCTIVE COATINGS

### OPTICS

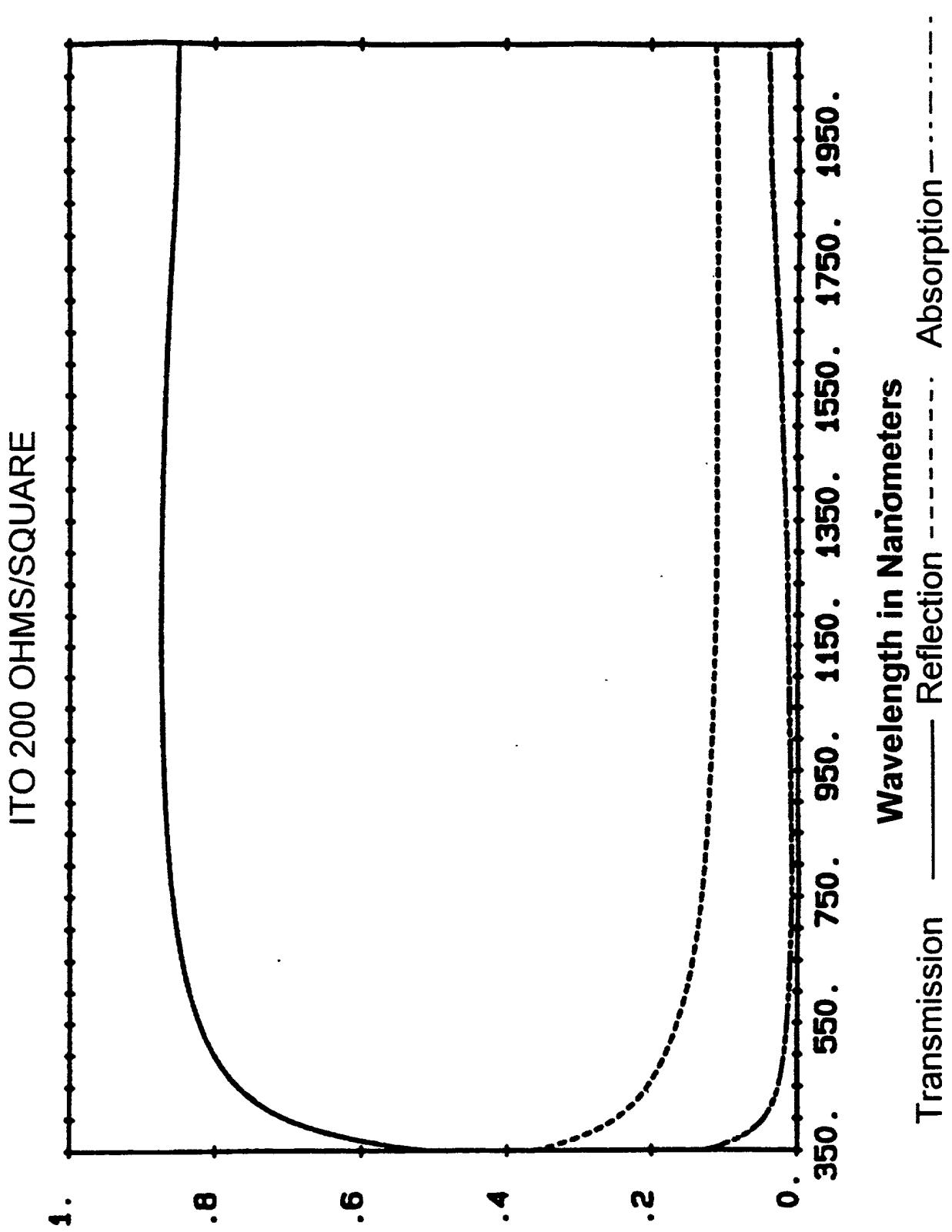


# PHYSICS FUNDMENTALS OF TRANSPARENT CONDUCTIVE COATINGS

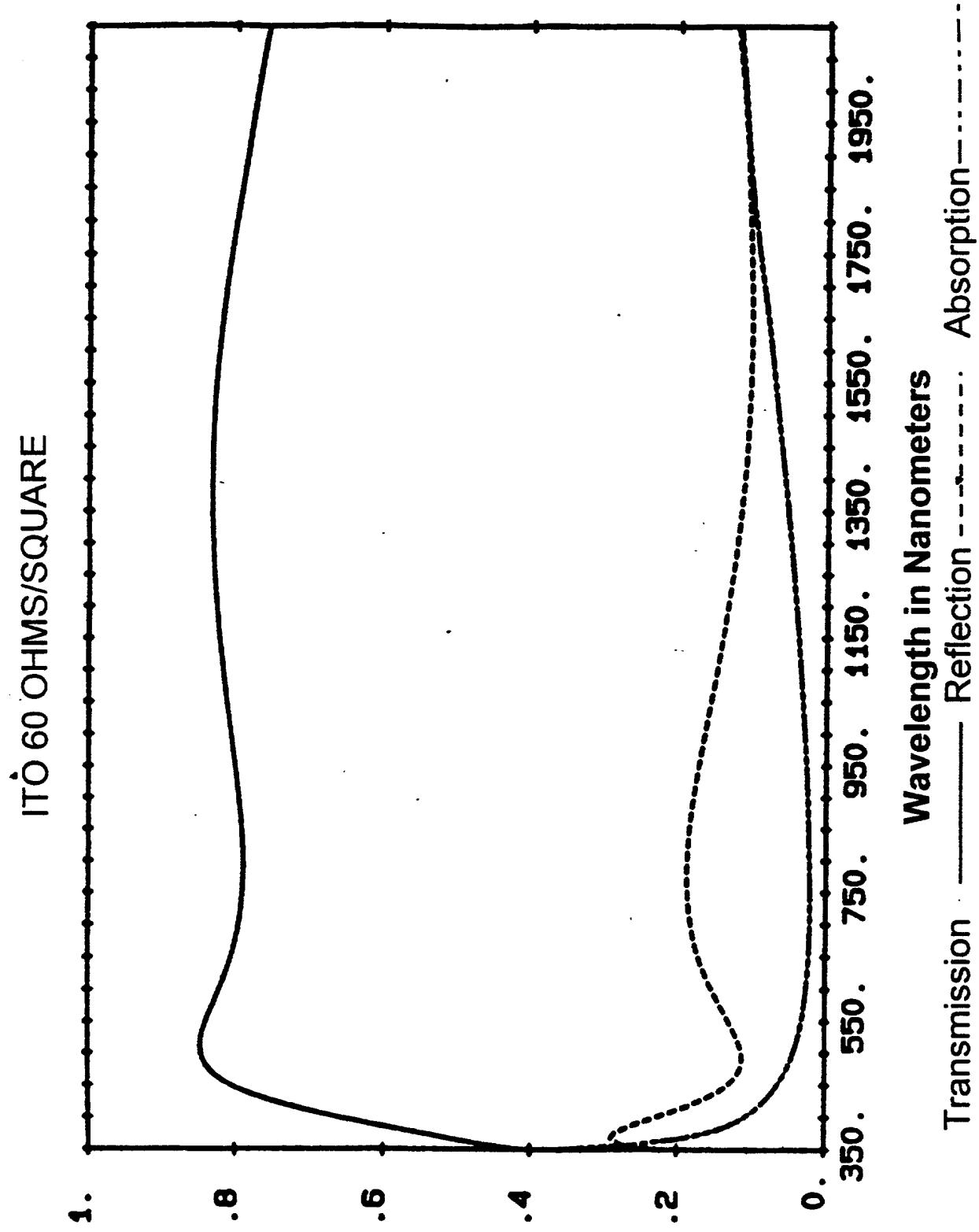
Color	<u>COLOR</u>			
	1 <sup>ST</sup> Order t(Å)	2 <sup>nd</sup> Order t(Å)	3 <sup>rd</sup> Order t(Å)	4 <sup>th</sup> Order t(Å)
Gray	75			
Tan	230			
Brown	380			
Blue	620			
Violet	770	2100	3600	5000
Blue	1150	2300	3800	5300
Green	1400	2500	4000	5550
Yellow	1600	2850	4300	5800
Orange	1750	3100	4600	6050
Red	1900	3350	4800	6300

<sup>a</sup>  $n = 2.00$ .

**Colors of TCO Thin Films When Viewed in Reflected White Light.**  
(From J.L. Vossen, Physics of Thin Films, Vol. 9, Academic Press, 1997)

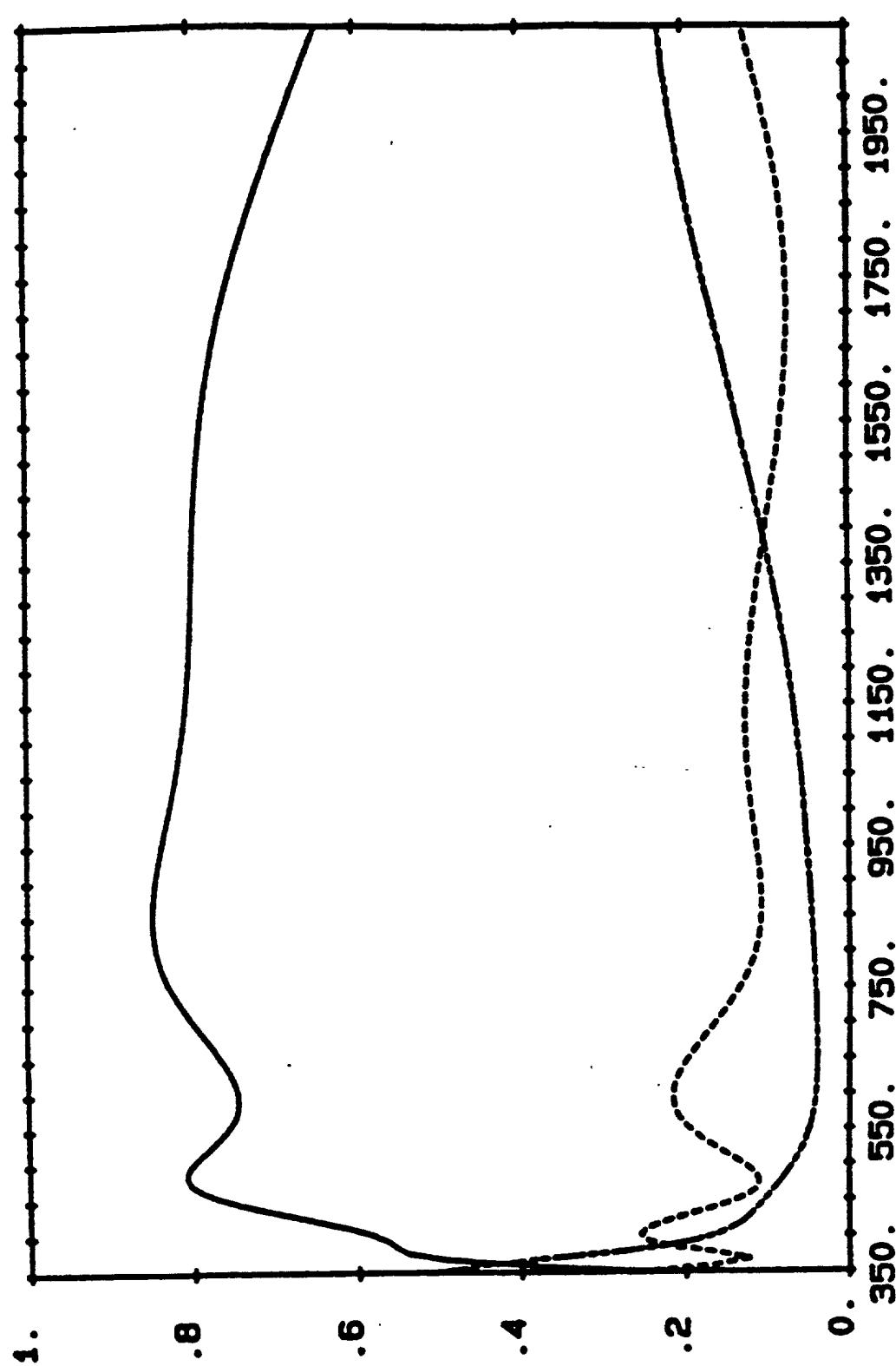


30



TRANSMISSION ABSORPTION REFLECTION

ITO 30 OHMS/SQUARE



Wavelength in Nanometers

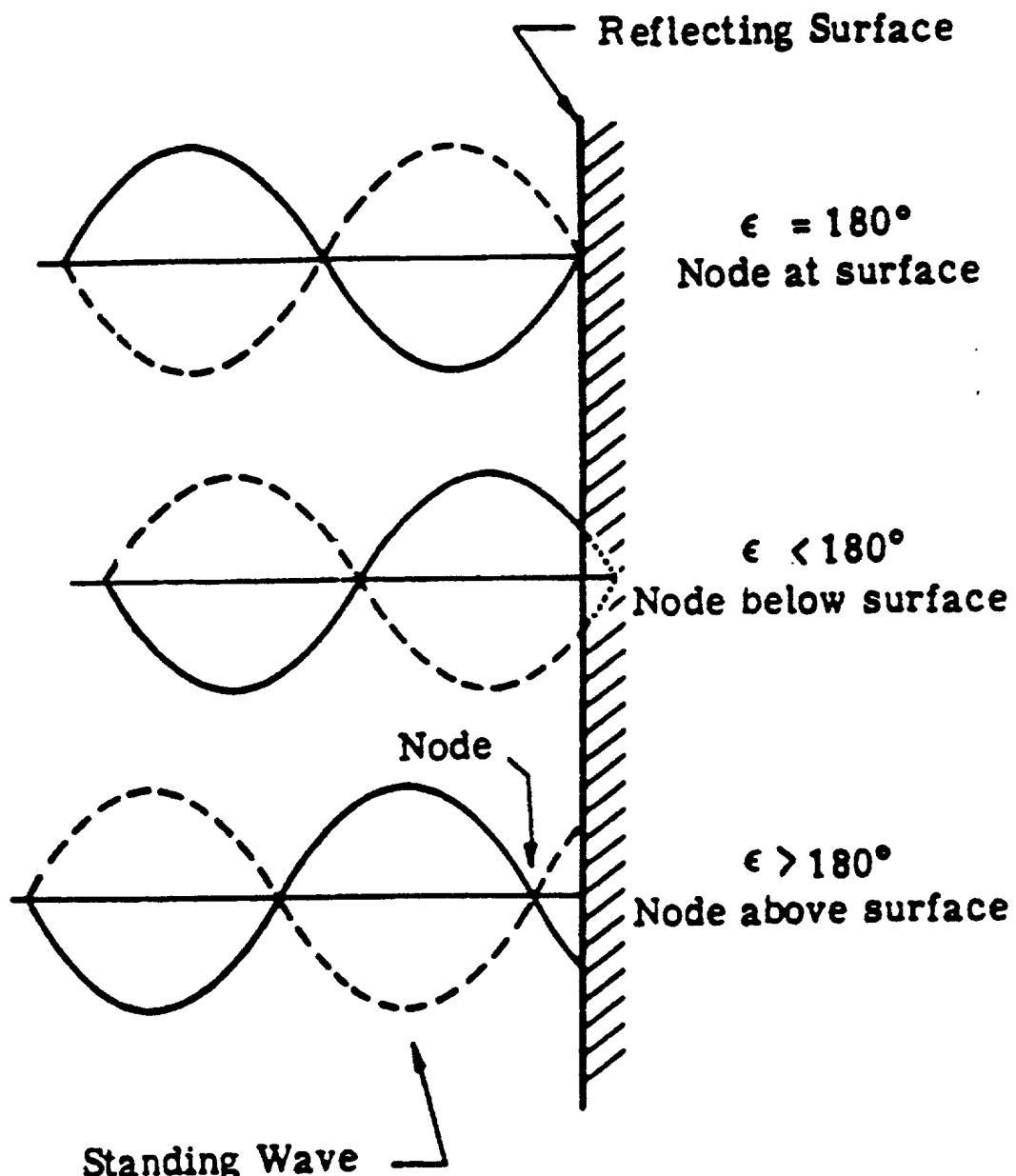
Transmission

Reflection

Absorption

# PHYSICS FUNDAMENTAL OF TRANSPARENT CONDUCTIVE COATINGS

## Thin Film Optics

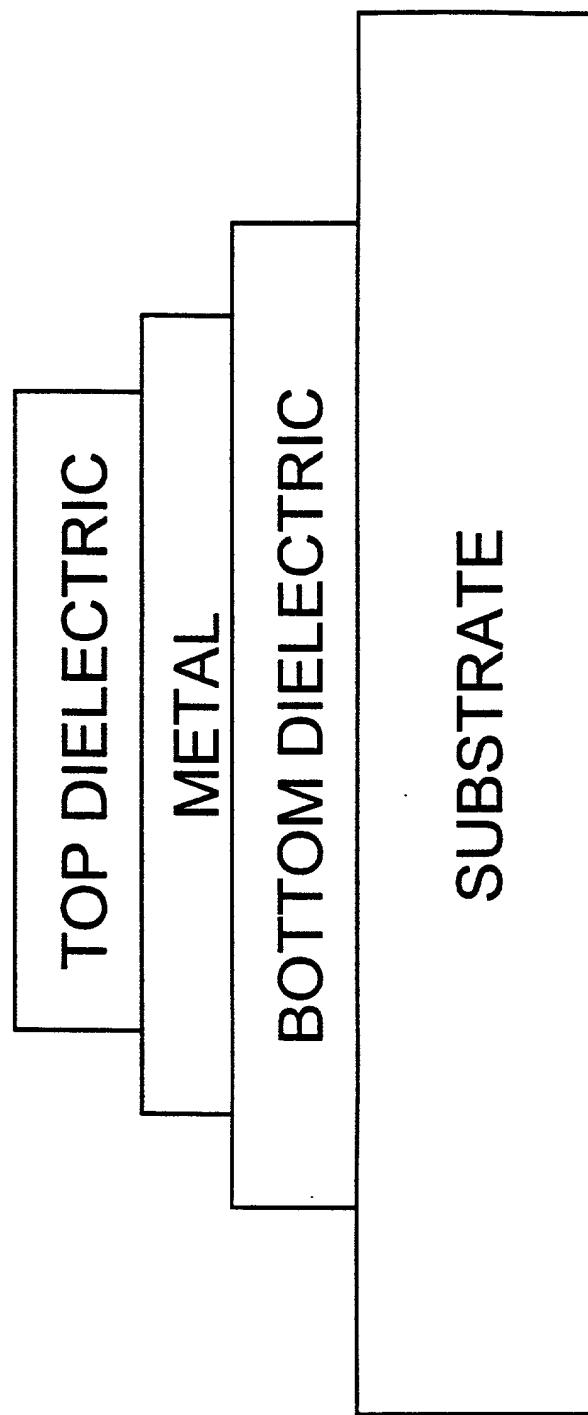


## Phase Shift upon Reflection and Standing Wave

(From Mil. Std. Handbook, Optical Design, Mil - Hdbk - 141, 1962)

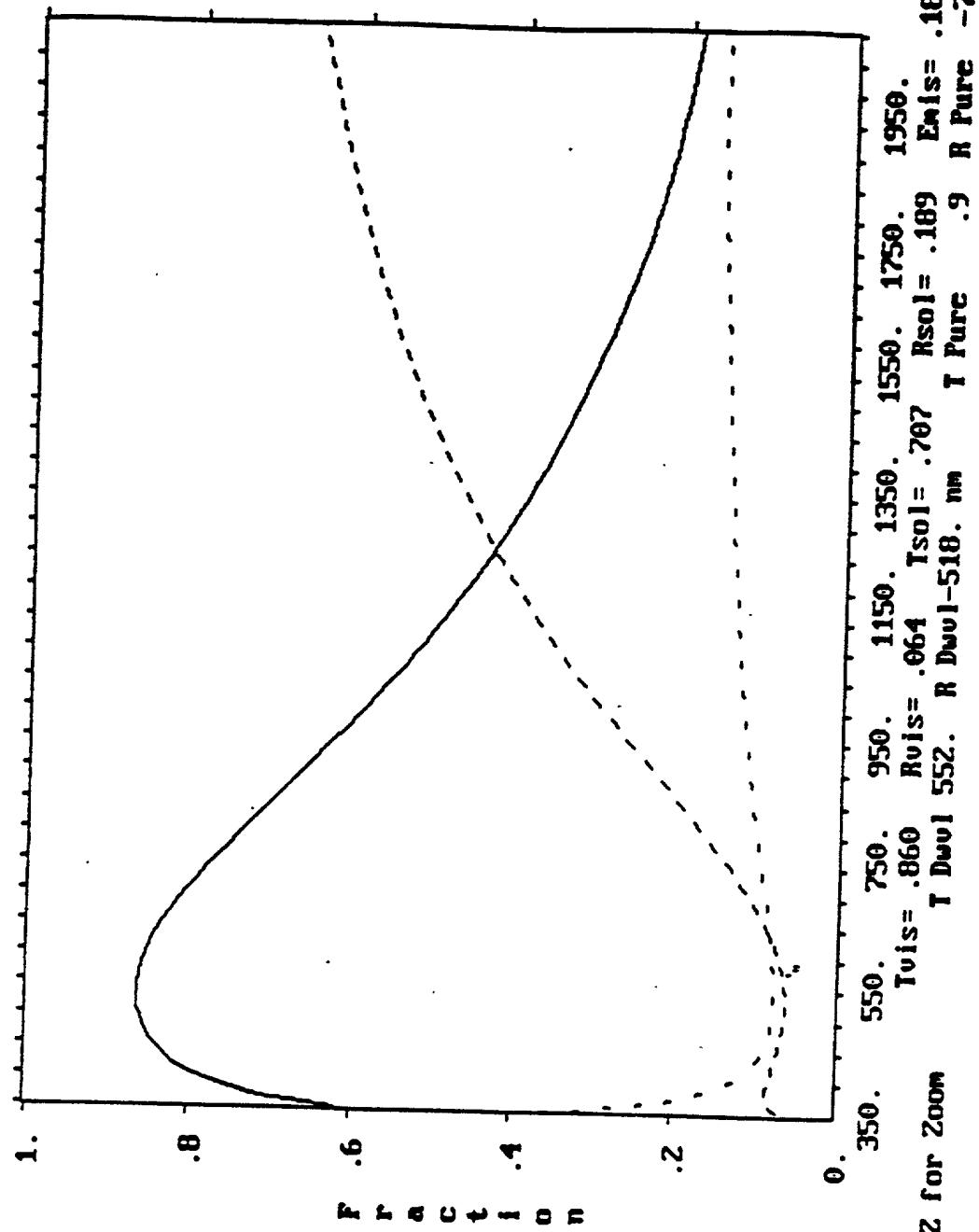
# **PHYSICS FUNDAMENTALS OF TRANSPARENT CONDUCTIVE COATINGS**

## **THIN FILM OPTICS**



T Gage 300 300 300 300

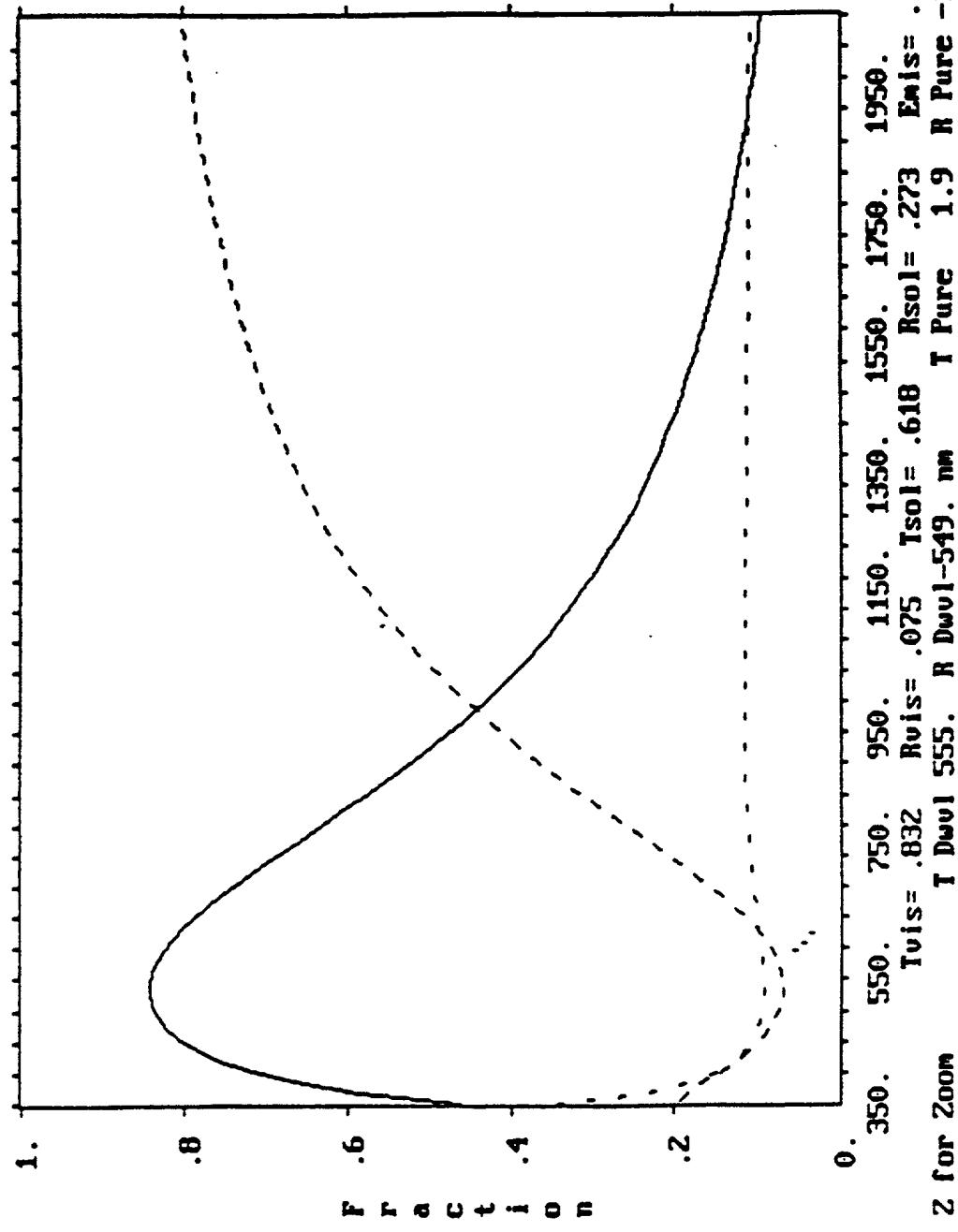
## OPTICALLY ENHANCED METAL



Metal Oxide - Silver - Metal Oxide Coating on PET, 20 Ohms/Square  
Transmittance - upper trace, Reflectance - middle trace, Absorptance - lower trace

Y GND ECD = 80016 81660

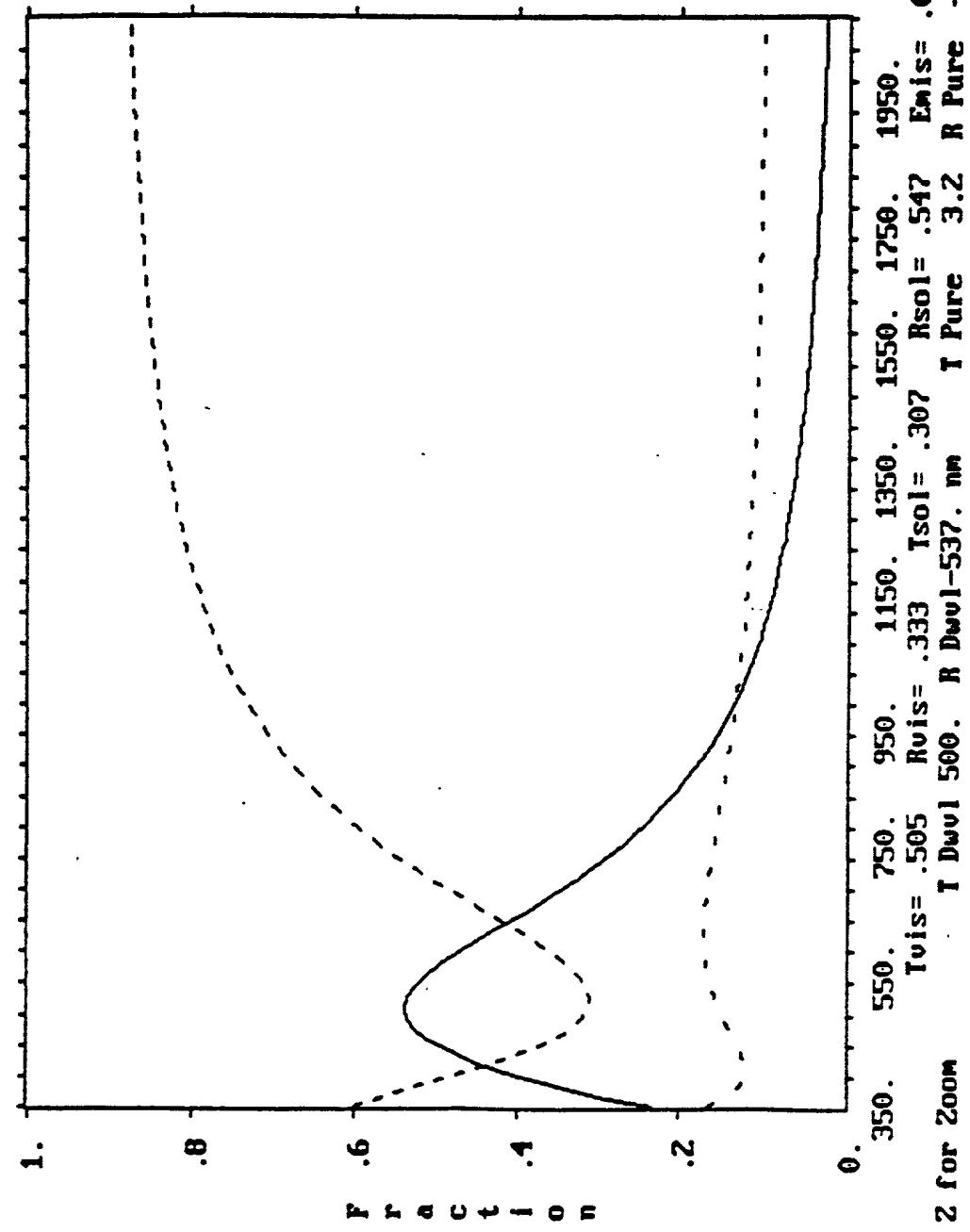
### OPTICALLY ENHANCED METAL



Metal Oxide - Silver - Metal Oxide Coating on PET, 10 Ohms/Square  
Transmittance - upper trace, Reflectance - middle trace, Absorptance - lower trace

32

## OPTICALLY ENHANCED METAL



Metal Oxide – Silver – Metal Oxide Coating on PET, 5 Ohms/Square  
Transmittance – upper trace, Reflectance – middle trace, Absorbance – lower trace

## PHYSICS FUNDAMENTALS OF TRANSPARENT CONDUCTIVE COATINGS

### OPTICAL AND ELECTRICAL PERFORMANCE

- A COMPROMISE BETWEEN HIGH OPTICAL TRANSMITTANCE AND HIGH CONDUCTIVITY (LOW RESISTIVITY) IS ALWAYS REQUIRED
- OPTICAL TRANSMITTANCE IS FUNDAMENTALLY LIMITED BY ABSORPTION
- OPTICAL TRANSMITTANCE AND REFLECTANCE ARE WAVELENGTH DEPENDENT
- OPTICAL PERFORMANCE CAN BE GENERALIZED BY TYPE OF TCC (i.e. METAL OR SEMICONDUCTOR) AND WAVEBAND (UV, VIS, NEAR IR, MIDWAVE IR AND LONGWAVE IR)
- MANY FIGURES-OF-MERIT FOR TCC HAVE BEEN DEFINED BUT LIMITED USEFULNESS BECAUSE NEED TO BE APPLICATION SPECIFIC

## SPECIFYING AND SELECTING TRANSPARENT CONDUCTIVE COATINGS

### FUNCTION

#### TRANSPARENT ELECTRODE:

- REQUIREMENT IS TO APPLY AN ELECTRICAL FIELD
- THEREFORE, COMPROMISE IS FOR HIGH TRANSMITTANCE WITH LOW CONDUCTIVITY (HIGH RESISTIVITY)

#### ELECTROMAGNETIC INTERFERENCE SHIELD:

- REQUIREMENT IS TO REFLECT EM WAVES WITH SPECIFIED FREQUENCIES
- SHIELDING EFFECTIVENESS IS INVERSELY PROPORTIONAL TO SURFACE RESISTIVITY, i.e., LOW OHMS/SQUARE GIVES HIGH SHIELDING
- COMPROMISE IS FOR LOW RESISTIVITY WITH ACCEPTABLE TRANSMITTANCE

# SPECIFYING AND SELECTING TRANSPARENT CONDUCTIVE COATINGS

## FUNCTION

### HEATER:

- REQUIREMENT IS FOR A RESISTANCE WHICH PERMITS ACHIEVING THE NEEDED POWER (DENSITY) FROM THE AVAILABLE VOLTAGE SOURCE
- TRANSMITTANCE CAN BE MAXIMIZED BY USE OF PART GEOMETRY AND CHOICE OF VOLTAGE SOURCE i.e. MORE THAN ONE OHMS/SQUARE CAN MEET RESISTANCE REQUIREMENT

### ANTISTATIC:

- REQUIREMENT IS TO DISCHARGE STATIC CHARGE NON-DESTRUCTIVELY
- RESISTANCE CAN BE HIGH AND STILL ACHIEVE ADEQUATE DISCHARGE TIMES
- THUS, OHMS/SQUARE CAN BE HIGH, WITH ATTENDANT HIGH TRANSMITTANCE

## SPECIFYING AND SELECTING TRANSPARENT CONDUCTIVE COATINGS

### FUNCTION

#### HEAT MIRROR:

- REQUIREMENT IS FOR HIGH SOLAR REFLECTANCE, LOW INFRARED (IR) EMISSIVITY AND MEDIUM LUMINOUS TRANSMITTANCE
  - HIGH FREE CARRIER DENSITY PRODUCES HIGH SOLAR AND INFRARED REFLECTANCE
  - PLASMA FREQUENCY SHOULD IDEALLY BE AT EDGE OF VISIBLE/NEAR IR WAVEBANDS
- #### CONDUCTIVE ANTIREFLECTION
- OPTICAL REQUIREMENT IS FOR LOW LUMINOUS REFLECTANCE AND LOW AVERAGE VISIBLE REFLECTANCE
  - CONDUCTIVE REQUIREMENTS IS FOR ANTISTATIC AND/OR ELECTROMAGNETIC INTERFERENCE SHIELDING
  - OPTICAL DESIGN DETERMINES TCC THICKNESS

## **TRANSPARENT CONDUCTIVE COATING DEPOSITION METHODS**

### **EVAPORATION**

#### **THERMAL:**

- NOBLE METALS (Ag, Au) AND TCO LIKE INDIUM OXIDE (IO), INDIUM TIN OXIDE (ITO) AND TIN OXIDE (TO) CAN BE DEPOSITED FROM REFRACTORY METAL BOATS, OR FILAMENTS AND FROM CERAMIC CRUCIBLES
- TYPICAL STARTING MATERIALS ARE METAL WIRES AND PIECES OR METAL OXIDE POWDERS (CHUNKS) AND PELLETS
- THE DIFFICULTY AND TEMPERATURE FOR EVAPORATION INCREASES WITH THE MATERIAL MELTING POINT
- OXYGEN BACKGROUND GAS USED FOR REACTIVE EVAPORATION OR TO MAKE UP FOR DISSOCIATION OF METAL OXIDES

## **TRANSPARENT CONDUCTIVE COATING DEPOSITION METHODS**

### **EVAPORATION**

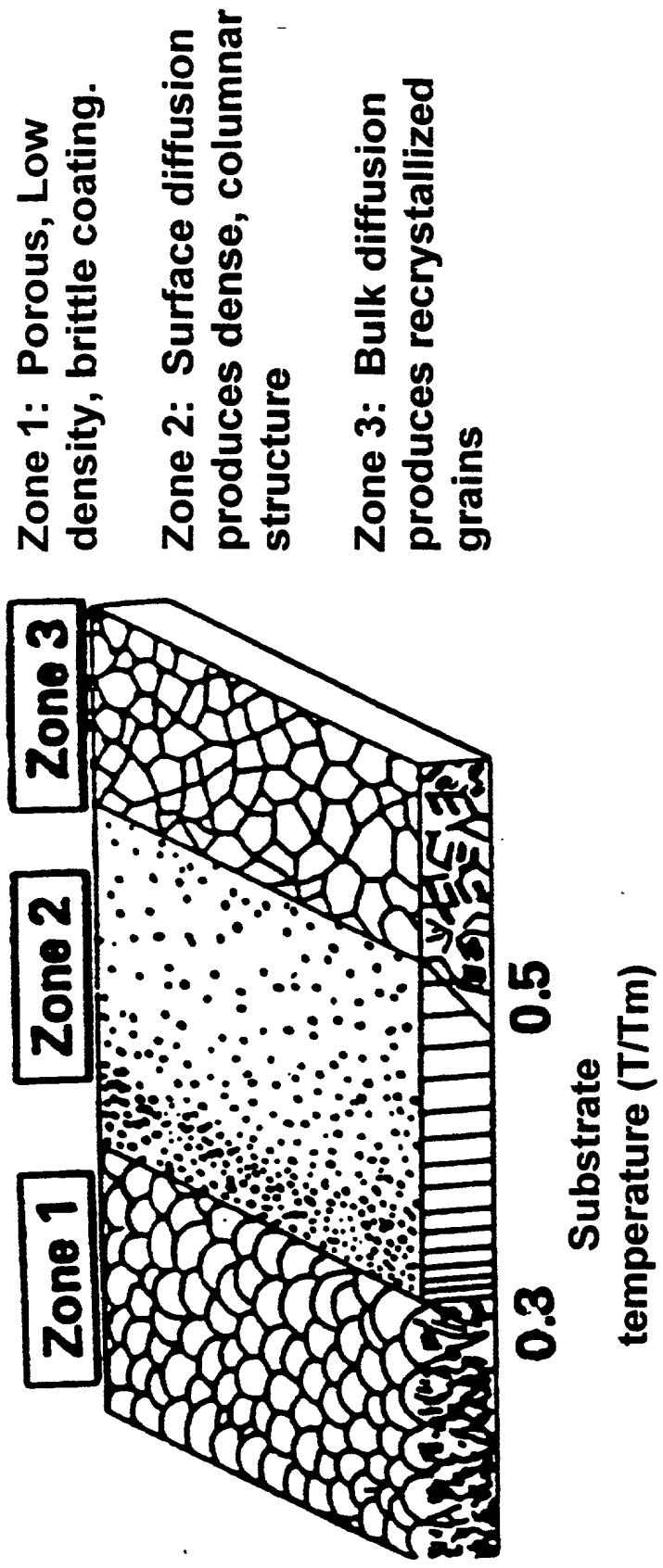
#### **ELECTRON – BEAM:**

- BOTH METALS AND METAL OXIDES CAN BE READILY EVAPORATED
- ITO OR TO DEPOSITED WITH EQUAL EASY
- OXYGEN GAS USED FOR REACTIVE EVAPORATION OR TO MAKE UP FOR DISSOCIATION OF METAL OXIDES

#### **PLASMA OR ION ASSISTED**

- DEPOSITION RATES CAN BE INCREASED
- FILM DENSITY AND REFRACTIVE INDEX INCREASED

## MICROSTRUCTURES OF EVAPORATED COATINGS



B.A. Movchan and A.V. Demshishin,  
Fiz. Metal. Metalloved., 28, part 2:83 (1969)

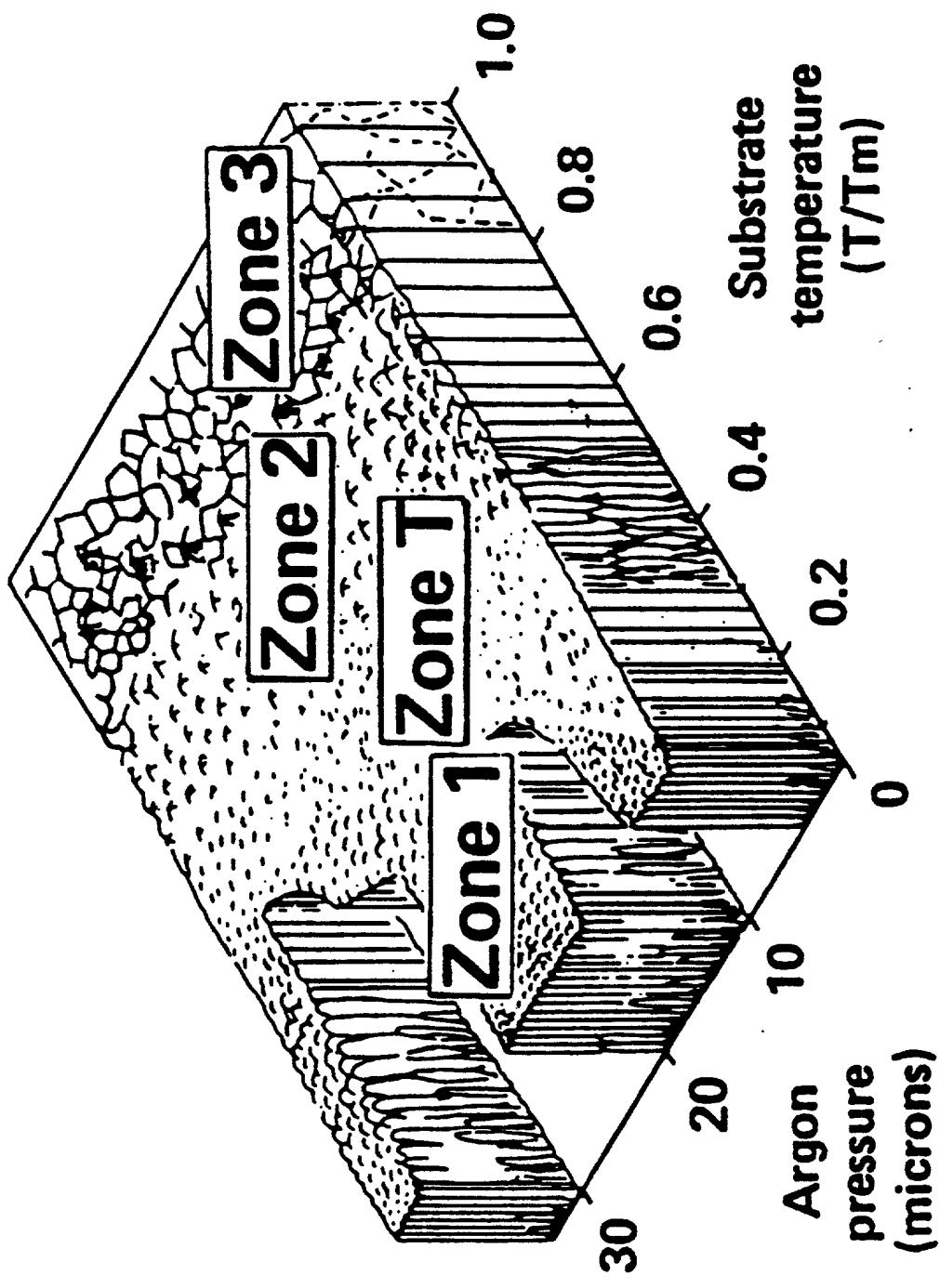
# **TRANSPARENT CONDUCTIVE COATING DEPOSITION METHODS**

## **SPUTTERING**

### **DC MAGNETRON – METALS**

- HIGH DEPOSITION RATES
- DENSE FILMS
- BULK LIKE REFRACTIVE INDEX

THORNTON STRUCTURE ZONE MODEL FOR  
SPUTTERED COATINGS



from J.A. Thornton, J. Vac. Sci. Technol; 11:666 (1974)

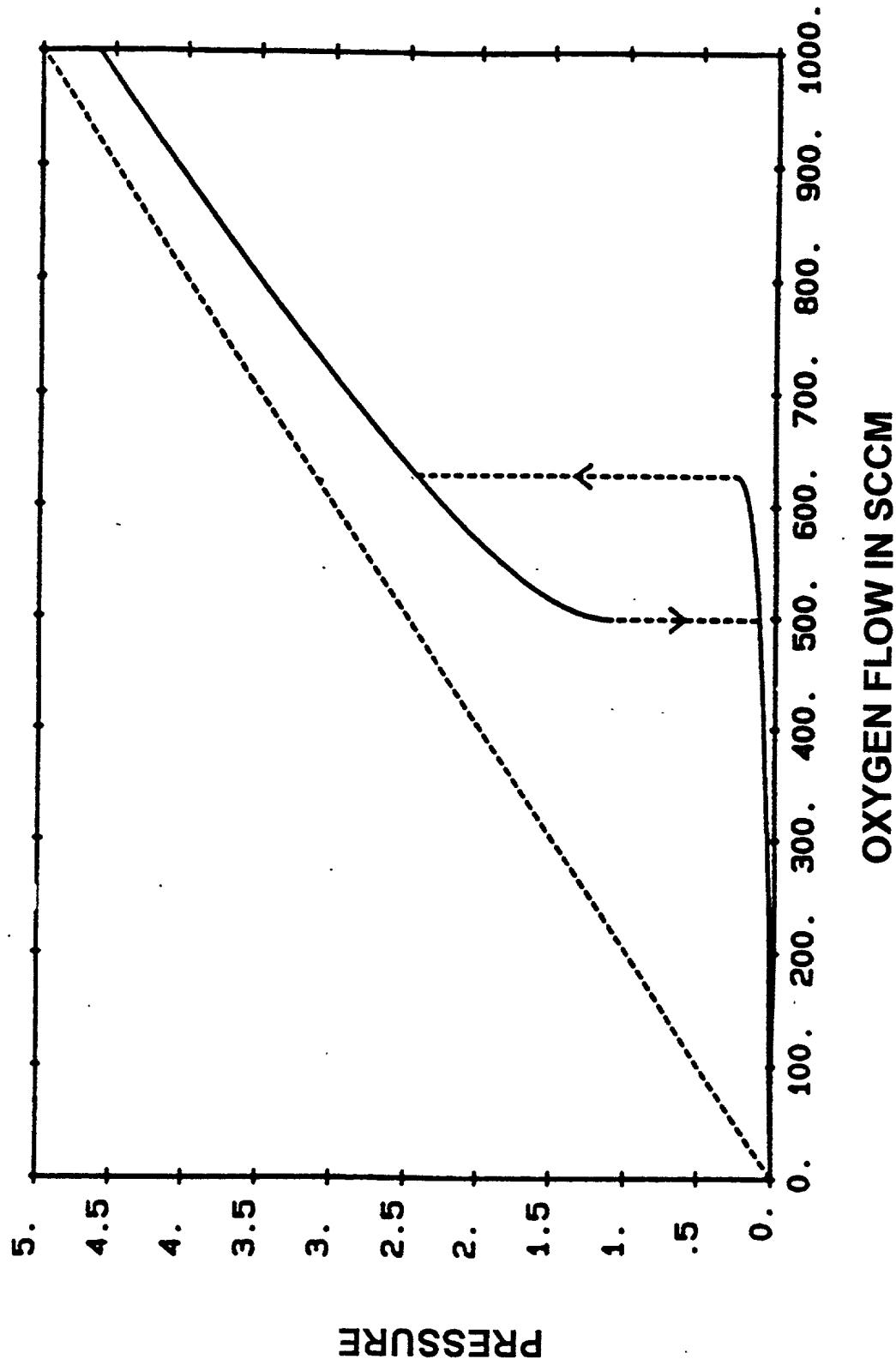
## TRANSPARENT CONDUCTIVE COATING DEPOSITION METHODS

### SPUTTERING

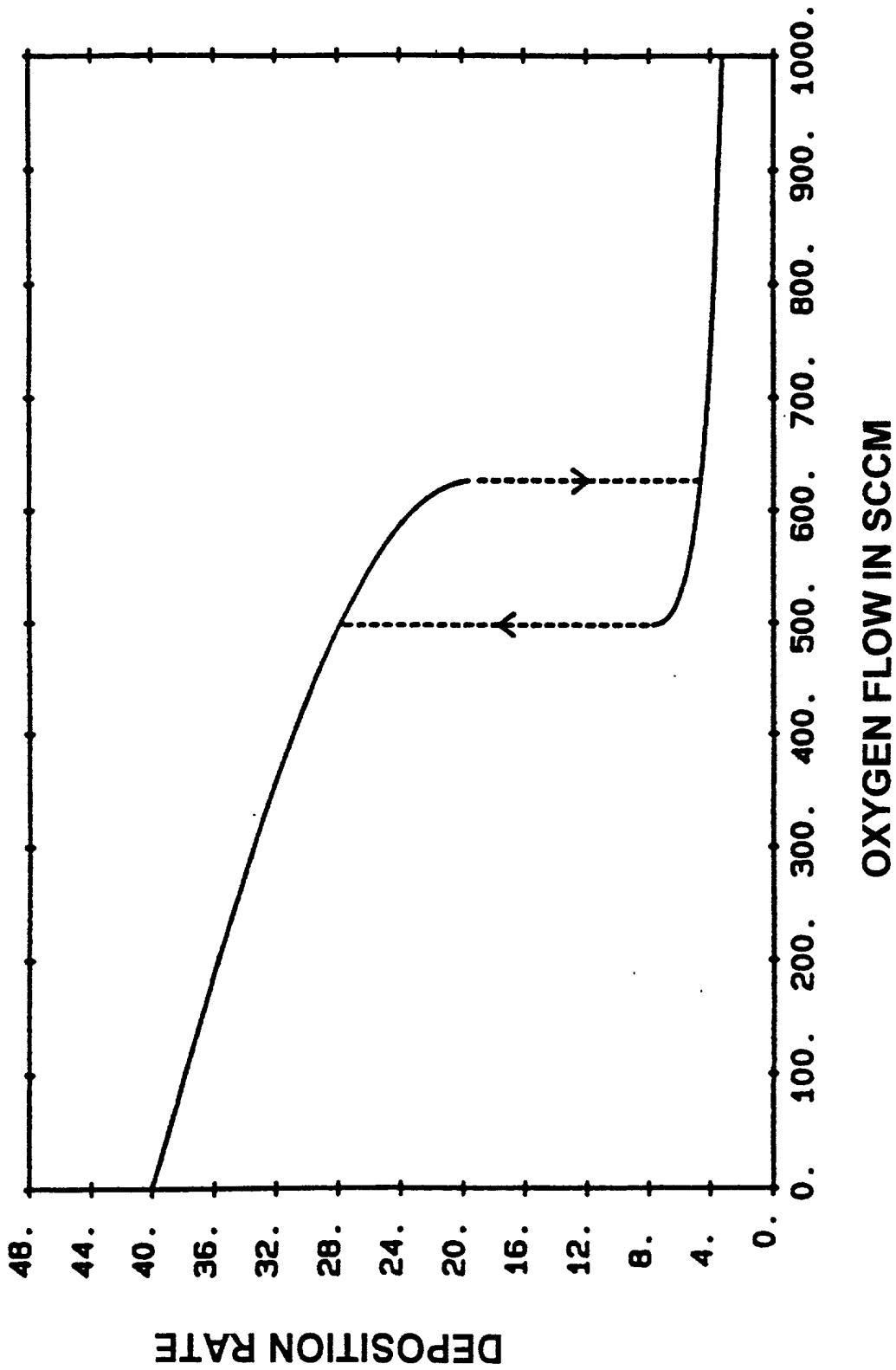
#### DC MAGNETRON - REACTIVE

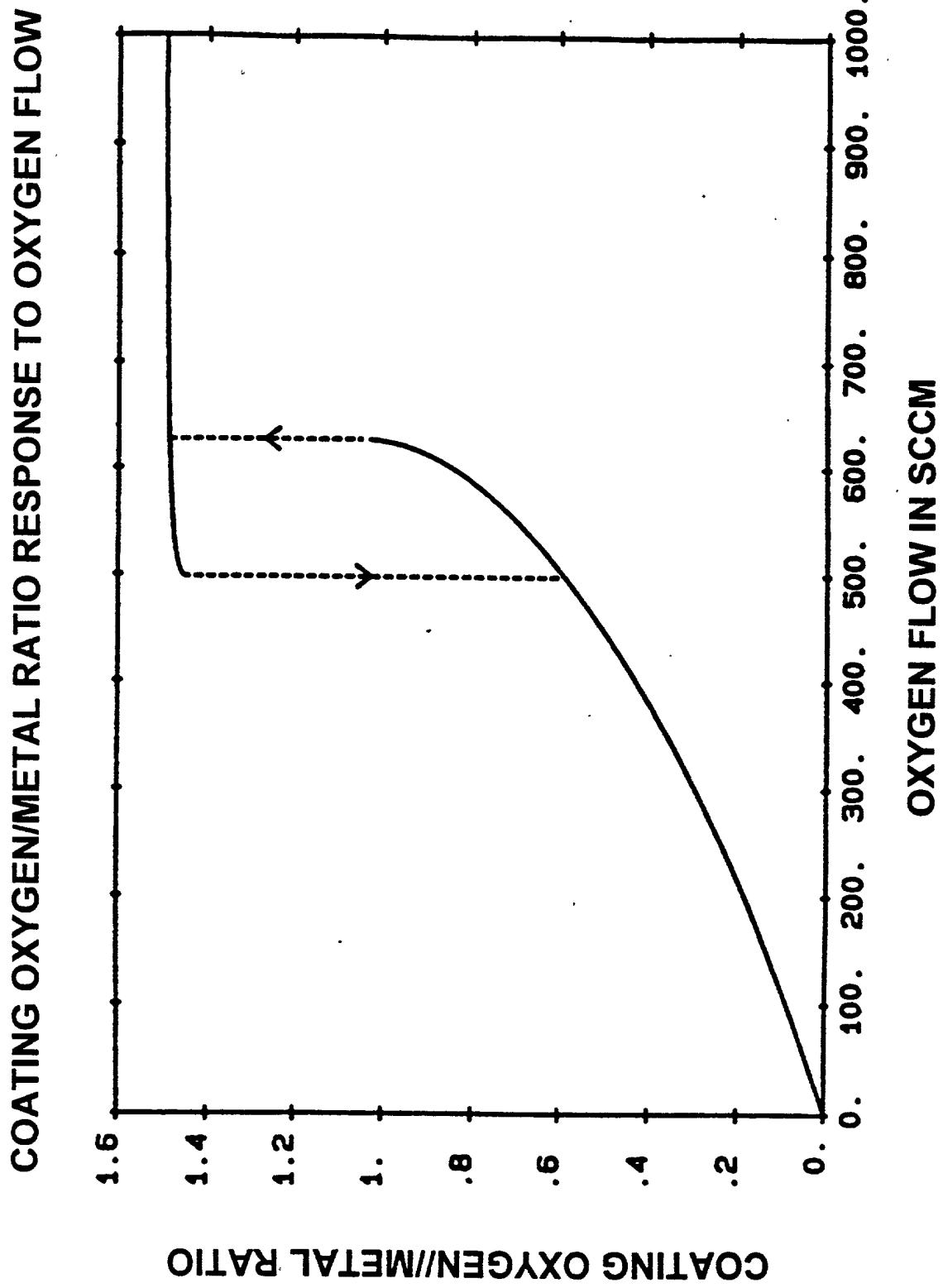
- REACTIVE SPUTTERING FROM METALLIC TARGETS TO DEPOSIT ITO, TO, ZINC OXIDE (ZO) ET AL
- HIGH DEPOSITION RATE IF TARGET IS KEPT FROM OXIDIZING
- ARCING AT OXIDIZED AREAS OF TARGET IS A PROBLEM

PRESSURE RESPONSE TO OXYGEN FLOW



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DEPOSITION RATE RESPONSE TO OXYGEN FLOW





## TRANSPARENT CONDUCTIVE COATING DEPOSITION METHODS

### SPUTTERING

#### DC MAGNETRON - SEMIREACTIVE

- SEMIREACTIVE SPUTTERING FROM CERAMIC TARGETS OF REDUCED IO, ITO, TO, ZO
- MUCH EASIER TO CONTROL THAN REACTIVE METAL PROCESS
- ARCING PROBLEM AND COATING DEFECTS REDUCED
- REQUIRES HIGHER POWER (DENSITY) THAN METAL TARGET FOR EQUIVALENT SPUTTERING RATES

## TRANSPARENT CONDUCTIVE COATING DEPOSITION METHODS

### SPUTTERING

#### RF SPUTTERING – DIODE OR MAGNETRON

- MAIN BENEFIT IS THAT TARGET MATERIALS NEED NOT HAVE DC CONDUCTIVITY
- MAIN DISADVANTAGE IS LOW DEPOSITION RATES
- EM SHIELDING OF EQUIPMENT REQUIRED
- SAFETY ISSUES

## TRANSPARENT CONDUCTIVE COATING DEPOSITION METHODS

### PYROLYSIS AND CHEMICAL VAPOR DEPOSITION (CVD)

#### PYROLYSIS - LIQUID

- CAN USE LOW COST MATERIALS
- MATERIALS AND REACTION PRODUCTS CAN BE HAZARDOUS
- DEPOSITION POSSIBLE AT ATMOSPHERIC PRESSURE
- TYPICALLY SPRAY PROCESS
- HIGH TEMPERATURE PROCESS

## TRANSPARENT CONDUCTIVE COATING DEPOSITION METHODS

### POST DEPOSITION PROCESSES

#### TCO POST PROCESSING

- BAKING IN VACUUM CAN REDUCE RESISTIVITY, IMPROVE CRYSTALLINITY, REDUCE INTRINSIC COATING STRESS
- BAKING IN OXIDIZING GAS CAN REDUCE ABSORPTION, INCREASE TRANSMITTANCE, IMPROVE DURABILITY, INCREASE RESISTIVITY, INCREASE REFRACTIVE INDEX
- BAKING IN AN INERT GAS CAN INCREASE REACTIVE INDEX, REDUCE COATING STRESS AND IMPROVE CRYSTALLINITY
- BAKING IN A REDUCING GAS CAN LOWER RESISTIVITY IMPROVE CRYSTALLINITY, REDUCE COATING STRESS, LOWER REFRACTIVE INDEX AND INCREASE ABSORPTION

## **TRANSPARENT CONDUCTIVE COATING DEPOSITION METHODS**

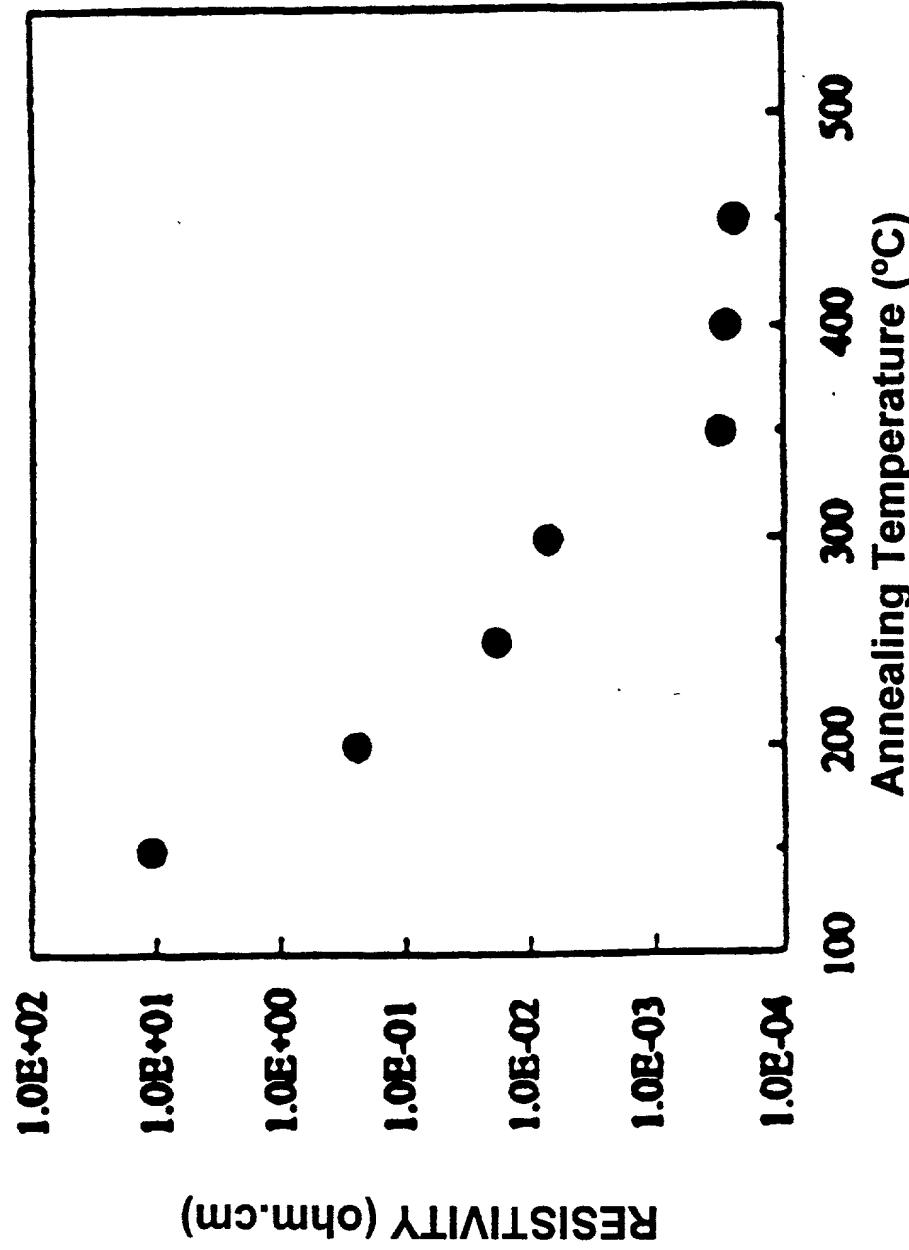
### **PYROLYSIS AND CHEMICAL VAPOR DEPOSITION (CVD)**

#### **LOW PRESSURE CVD - VAPOR**

- COATS ALL EXPOSED SURFACES
- COATINGS ARE VERY DURABLE
- DEPOSITION RATES CAN BE VERY HIGH
- MATERIALS AND REACTION PRODUCTS CAN BE HAZARDOUS
- HIGH TEMPERATURE PROCESS
- PLASMA ENHANCEMENT CAN REDUCE PROCESS TEMPERATURE

## TRANSPARENT CONDUCTIVE COATING DEPOSITION METHODS

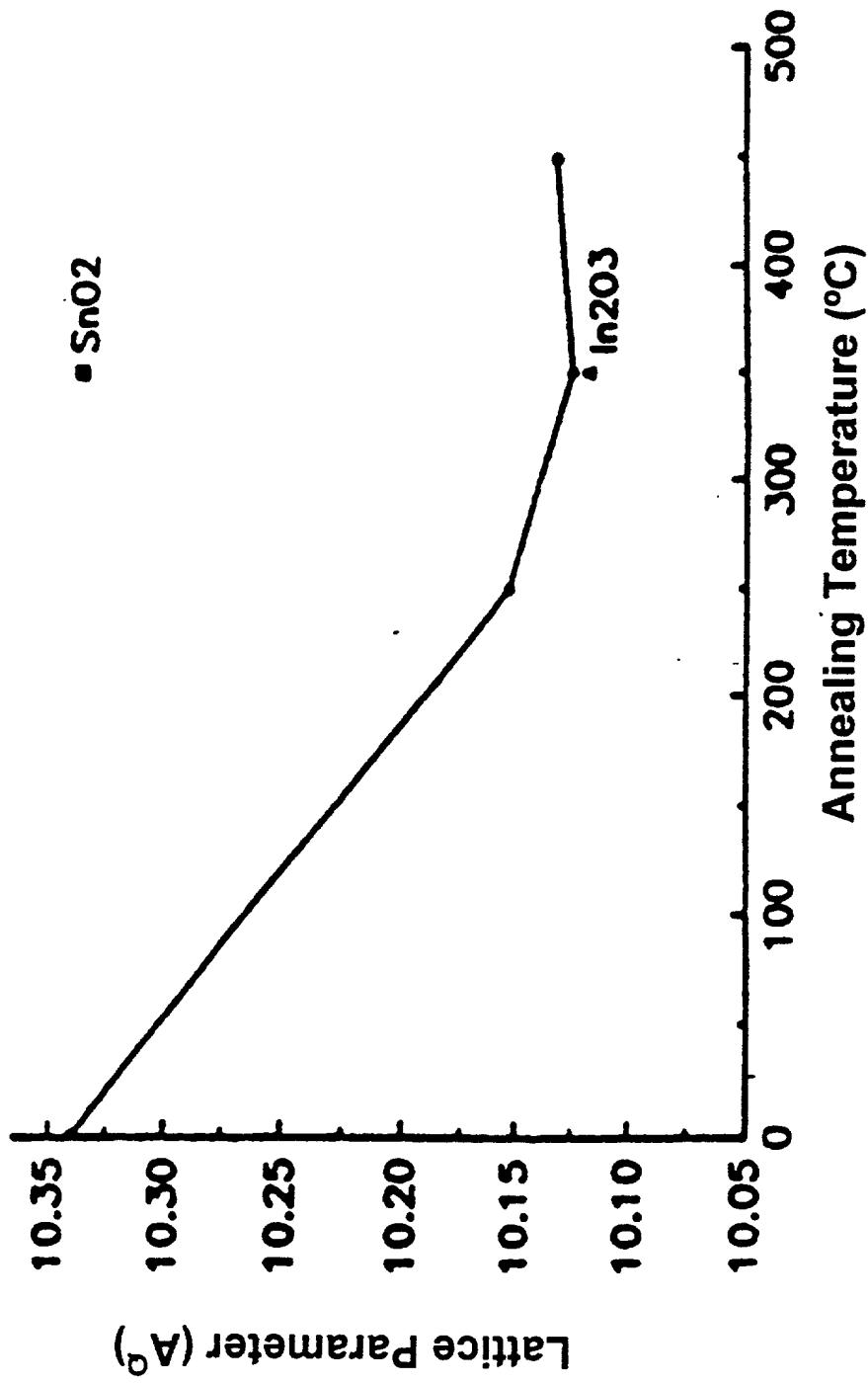
### POST DEPOSITION PROCESSES



Surface Resistivity Versus Vacuum Annealing Temperature (25 min.) for Sputtered ITO  
(From M. A. Martines, et al., *Thin Solid Films*, 269, (1995) 80-84)

## TRANSPARENT CONDUCTIVE COATING DEPOSITION METHODS

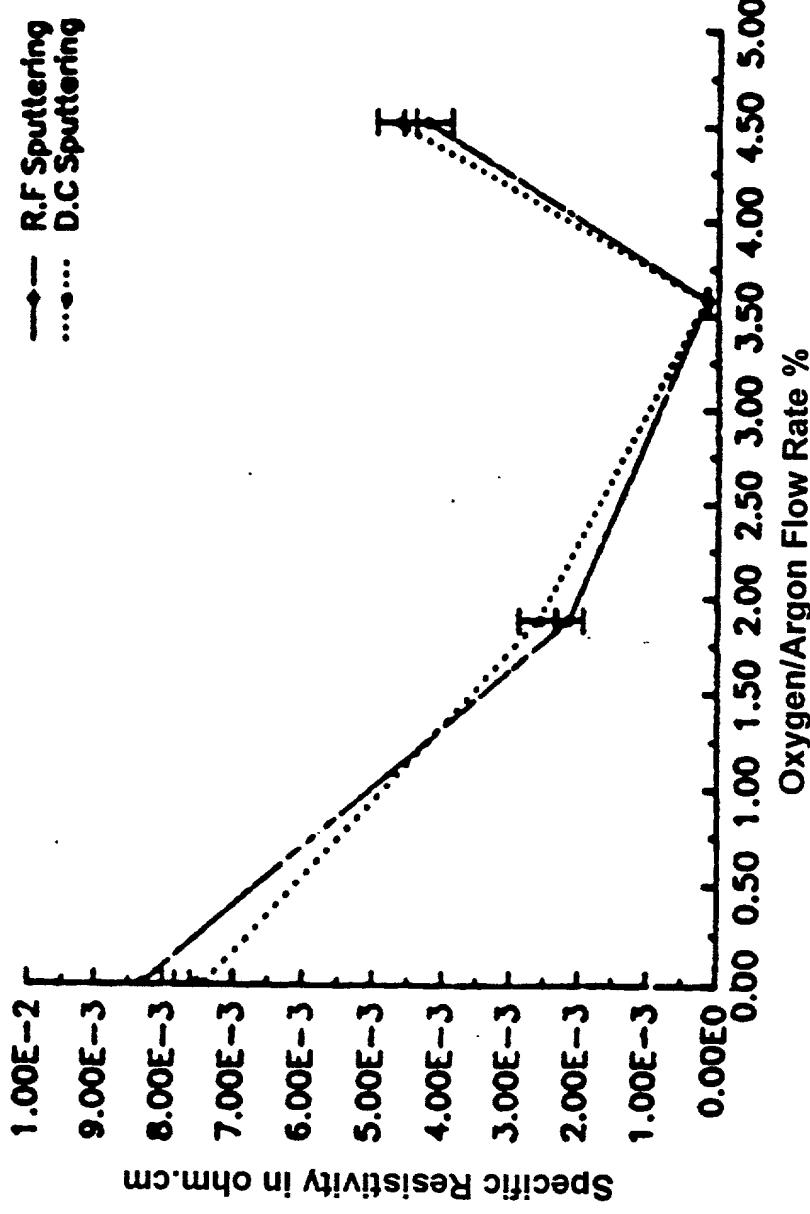
### POST DEPOSITION PROCESSES



Surface Resistivity Versus Annealing Temperature (24 min.) for Sputtered ITO  
(From M. A. Martins, et al., Thin Solid Films, 269, (1995) 80-84)

## TRANSPARENT CONDUCTIVE COATING DEPOSITION METHODS

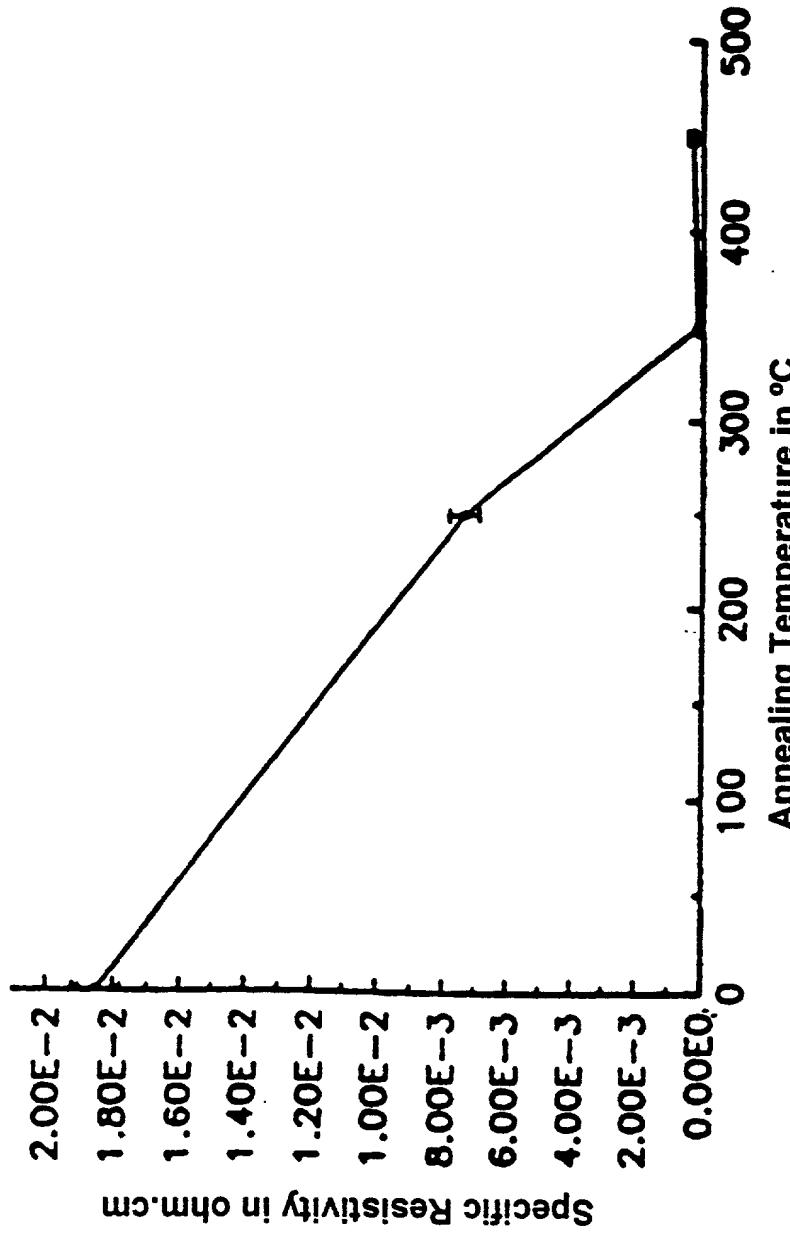
### POST DEPOSITION PROCESSES



Surface Resistivity for Sputtered ITO Films Annealed (2 hours in air) at 350°C as a Function of Oxygen/Argon Flow Rate during Sputtering  
(From R. N. Joshi, et al., *Thin Solid Films*, 257, (1995) 32-35)

# **TRANSPARENT CONDUCTIVE COATING DEPOSITION METHODS**

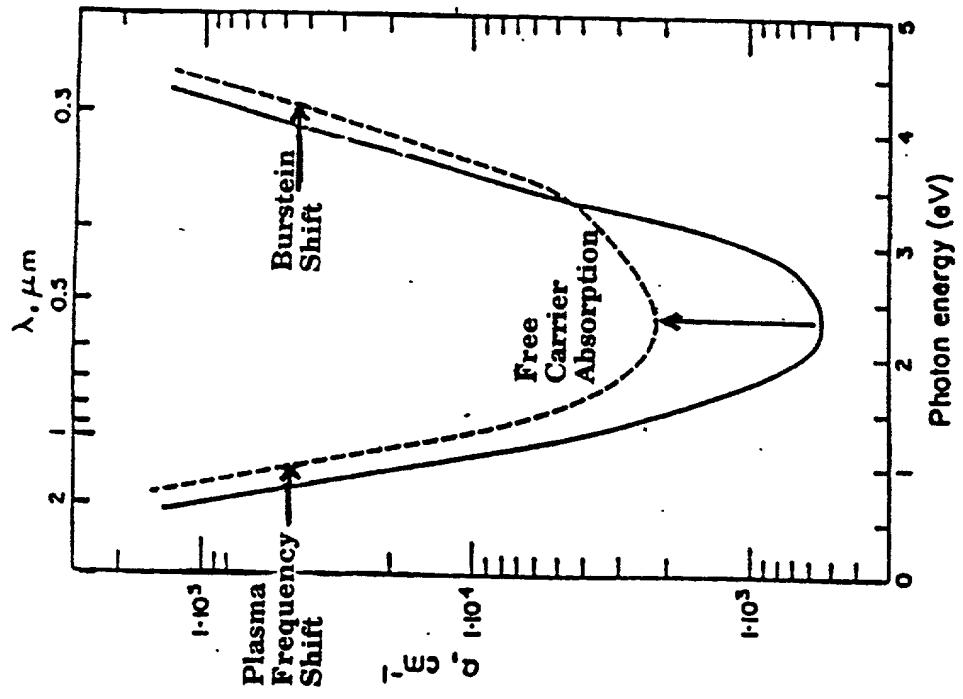
## **POST DEPOSITION PROCESSES**



**Surface Resistivity Versus Annealing Temperature (2 hours in air) for r.f. Sputtered ITO**

(From R. N. Joshi, et al., Thin Solid Films, 257, (1995) 32-35)

## Absorption as a Function of Photon Energy



**Solid line:** As deposited ITO film. ( $N = 5.8 \times 10^{20} / \text{cm}^3$ )

**Broken line:** After 30 min. at 400 C in  $N_2 + 10\% H_2$ .  
( $N = 11.2 \times 10^{20} / \text{cm}^3$ )

## IMPORTANT TCO VACUUM PROCESS PARAMETERS

### SUBSTRATE TEMPERATURE

- MAXIMIZING SUBSTRATE TEMPERATURE WILL IMPROVE CRYSTALLINITY WHICH INCREASE ELECTRON MOBILITY AND SCATTERING TIME
- A THRESHOLD TEMPERATURE IS REQUIRED TO ACTIVATE METAL, e.g. Sn, DOPANTS

### DEPOSITION RATE

- LOW PRODUCT COST DICTATES HIGH DEPOSITION RATES
- FOR SPUTTERING, HIGH RATES REQUIRES OPERATING IN THE METAL MODE
- HIGH DEPOSITION RATES MUST BE SUPPORTED BY HIGH REACTION RATES BETWEEN METAL ATOMS OR IONS AND OXYGEN ATOMS OR IONS

## IMPORTANT TCO VACUUM PROCESS PARAMETERS

### OXYGEN PARTIAL PRESSURE

- BECAUSE OXYGEN DEFICIENCY IS THE MAJOR CONTROL OF CONDUCTIVITY AND ABSORPTION, CONTROL IS CRITICAL

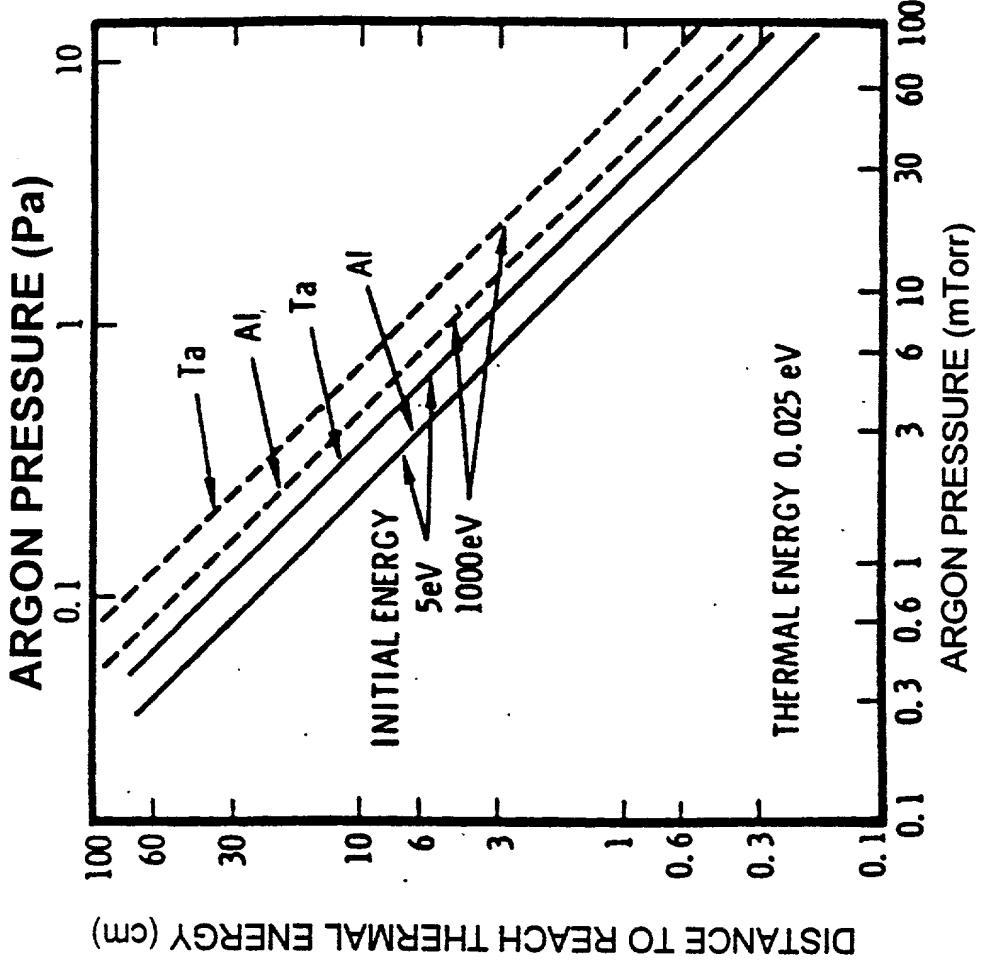
### CHAMBER PRESSURE

- LOWER CHAMBER PRESSURE MEANS ATOMS ARRIVE AT SUBSTRATE WITH MORE KINETIC ENERGY WHICH IMPROVES CRYSTALLINITY AND REDUCES DEFECTS
- IF PRESSURE IS TOO LOW, DEPOSITED FILM WILL BE REDUCED (METALLIC)
- IF PRESSURE IS TOO LOW, A SPUTTERING PROCESS CAN NOT BE MAINTAINED
- LOW CHAMBER PRESSURE PRODUCES MORE LINE-OF-SIGHT DEPOSITION

## IMPORTANT TCO VACUUM PROCESS PARAMETERS

### SOURCE TO SUBSTRATE DISTANCE

- SMALL SEPARATION PRODUCES MORE SUBSTRATE HEATING
- SMALL SEPARATION MEANS ATOMS AND IONS ARRIVE WITH MORE KINETIC ENERGY
- LARGE SEPARATION PRODUCES MORE LINE-OF-SIGHT DEPOSITION
- LARGE SEPARATION ALLOWS MORE TIME FOR REACTION WITH OXYGEN IN CHAMBER



Maximum distance from the target at which sputtered Al and Ta atoms of different initial energies are thermalized in Ar at various pressures. Thermalized energy assumed to be 0.025 eV.

W.D. Westwood, J. Vac. Sci. Technol. **15**, 188 (1978).

## **DEVELOPING AN ITO PROCESS**

### **SELECTING THE DEPOSITION PROCESS**

- DEPOSITION PROCESS MAY BE DICTATED BY AVAILABLE EQUIPMENT
- COATING APPLICATION MAY FAVOR A PARTICULAR DEPOSITION TECHNOLOGY
- TYPE OF SUBSTRATE CAN INFLUENCE DEPOSITION PROCESS CHOICE
- COATING DENSITY AND DURABILITY MAY INFLUENCE PROCESS CHOICE

## **DEVELOPING AN ITO PROCESS**

### **STARTING MATERIAL CHOICE**

- AFTER DEPOSITION PROCESS IS CHOSEN, STARTING MATERIAL CHOICES ARE REDUCED
- COST/PERFORMANCE CONSIDERATION
- CONVENIENCE AND AVAILABILITY ISSUES
- APPLICATION REQUIREMENTS USUALLY MAJOR FACTOR IN SELECTING TYPE AND FORM OF STARTING MATERIAL

## DEVELOPING AN ITO PROCESS

### CHOOSING SUBSTRATE TEMPERATURE

- FROM COATING PERFORMANCE CONSIDERATIONS ALONE -  
“HOTTER IS BETTER”
- EQUIPMENT LIMITATIONS MAY DICTATE MAXIMUM TEMPERATURE
- THERMAL LIMITATIONS OF SUBSTRATE MAY DETERMINE PROCESS TEMPERATURE
- COST/PERFORMANCE TRADE-OFFS CAN INFLUENCE TEMPERATURE SELECTION

## **DEVELOPING AN ITO PROCESS**

### **SELECTING ITO THICKNESS**

- ITO THICKNESS RANGE USUALLY DETERMINED BY COATING FUNCTION
- OPTICAL REQUIREMENTS CAN DETERMINE ALLOWED THICKNESS(ES)
- OPTICAL VERSUS ELECTRICAL PERFORMANCE TRADE OFF
- COST, POST PROCESSING SPEED, COATING STRESS AND DURABILITY ARE FACTORS
- COATING ENVIRONMENTAL REQUIREMENTS, e.g. TEMPERATURE CYCLING, CAN INFLUENCE CHOICE

## DEVELOPING AN ITO PROCESS

### DETERMINING THE RESISTIVITY "WELL"

- NOW THAT THE TYPE OF DEPOSITION PROCESS, STARTING MATERIAL, SUBSTRATE TEMPERATURE AND ITO THICKNESS HAVE BEEN SELECTED, DETERMINE THE INFLUENCE OF OXYGEN FLOW RATE/PARTIAL PRESSURE ON (SURFACE) RESISTIVITY
- AT LOW CHAMBER PRESSURE, WITH A CONSTANT DEPOSITION RATE (POWER SETTING) ADD OXYGEN UNTIL CHAMBER PRESSURE JUST BEGINS TO RISE, (OPEN SHUTTER, CHANGE MONITOR CHIP), DEPOSIT A SAMPLE UNTIL DESIRED THICKNESS IS ACHIEVED
- IF POSSIBLE, CLOSE SHUTTER, CHANGE CHIP, INCREMENT OXYGEN FLOW RATE AND REPEAT DEPOSITION STEP
- OTHERWISE, BREAK VACUUM REMOVE PART, RELOAD CHAMBER AND REPEAT DEPOSITION STEP AT NEW OXYGEN FLOW RATE
- AFTER SEVERAL DEPOSITIONS AT HIGHER AND LOWER OXYGEN FLOW RATES, PLOT MEASURED RESISTIVITY VERSUS OXYGEN FLOW RATE TO DETERMINE "WELL"

# INDIUM TIN OXIDE CERAMIC TARGET

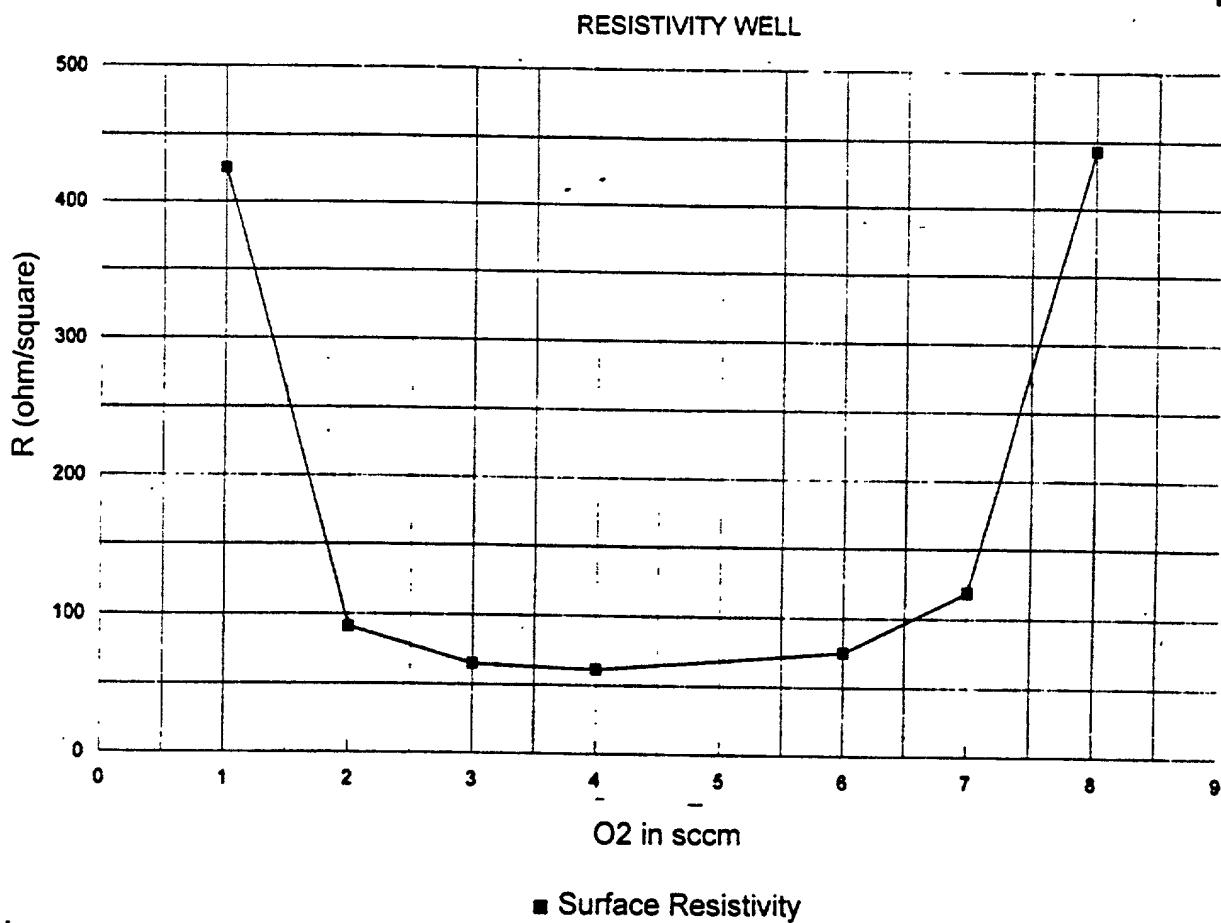
TARGET: 90 wt. % In<sub>2</sub>O<sub>3</sub> / 10 wt. % SnO<sub>2</sub>

Date: 04-09-96

SUBSTRATE: Glass Slide

CONDITIONS:  
no heat  
power .50 KW  
speed 5.75 inch/min.  
total flow 50 sccm  
pressure 1.8 – 1.9 microns

O <sub>2</sub> (sccm)	1	2	3	4	6	7	8
R (ohms/square)	425	91.3	64.9	61.05	75	119	443
%T vis (Luminous)	66.8	80.6	84.9	87.1	87.8	86.3	83.3
thickness (nm, slide)	102.6	96.3	107.5	94.3	93.3	99.9	100.5
rho (x1.0E-4 ohm-cm)	43.6	8.8	7.0	5.8	7.0	11.9	44.5



# INDIUM TIN OXIDE CERAMIC TARGET

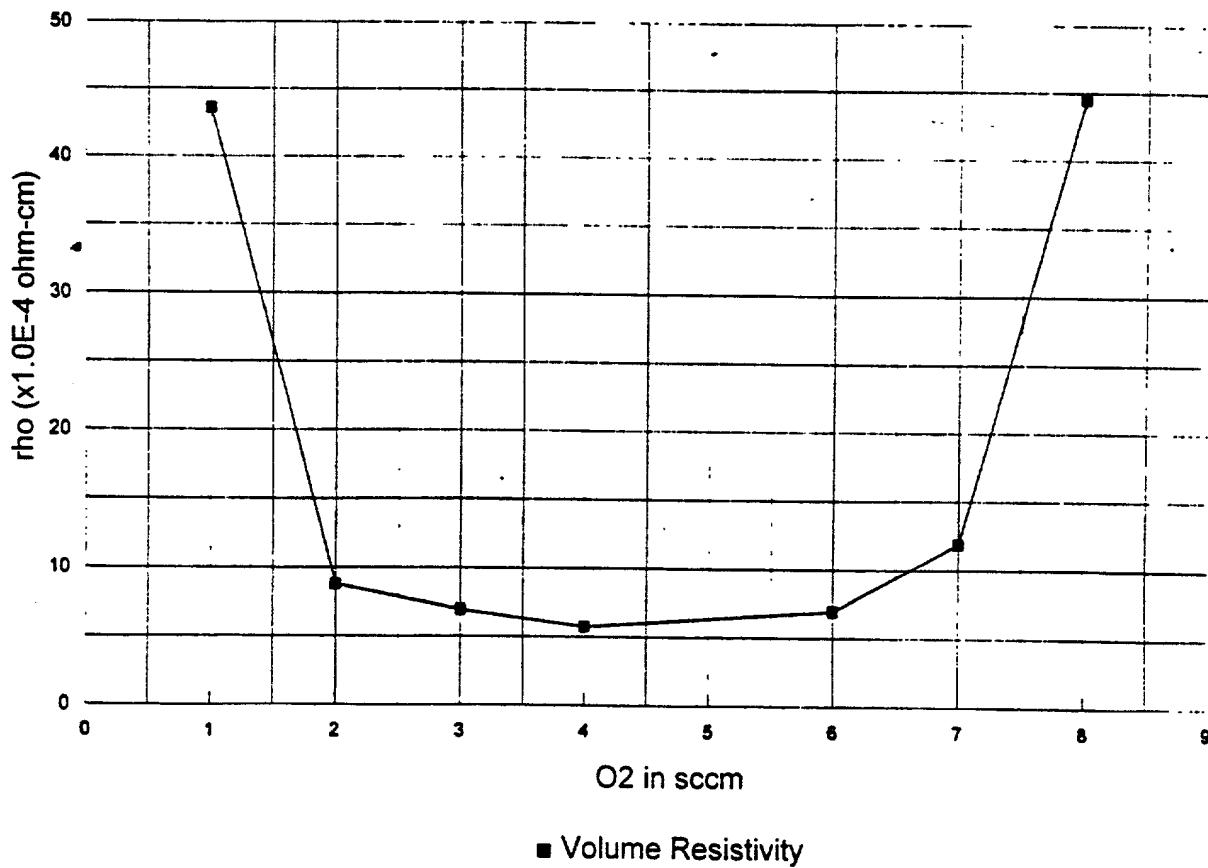
TARGET: 90 wt. % In<sub>2</sub>O<sub>3</sub> / 10 wt. % SnO<sub>2</sub> Date: 04-09-96

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pressure 1.8 – 1.9 microns

O <sub>2</sub> (sccm)	1	2	3	4	6	7	8
R (ohms/square)	425	91.3	64.9	61.1	75	119	443
%T vis (Luminous)	66.8	80.6	84.9	87.1	87.8	86.3	83.3
thickness (nm, slide)	102.6	96.3	107.5	94.3	93.3	99.9	100.5
rho (x1.0E-4 ohm-cm)	43.6	8.8	7.0	5.8	7.0	11.9	44.5

RESISTIVITY WELL



■ Volume Resistivity

## DEVELOPING AN ITO PROCESS

### SELECTING OPTICAL VERSUS ELECTRICAL PERFORMANCE

- DETERMINE SPECTRAL TRANSMITTANCE, REFLECTANCE AND ABSORPTANCE OF COATINGS DEPOSITED TO DETERMINE RESISTIVITY "WELL"
- CALCULATE INTEGRATED OPTICAL VALUES OF INTEREST TO APPLICATION, e.g., LUMINOUS TRANSMITTANCE, FOR EACH SAMPLE AND PLOT VERSUS OXYGEN FLOW RATES
- FROM PLOTS OF SPECTRAL AND INTEGRATED OPTICAL VALUES, AND RESISTIVITY, SELECT FLOW RATE (PRESSURE) FOR PROCESS WHICH OPTIMIZES COMPROMISE AMONG REQUIREMENTS

# INDIUM TIN OXIDE CERAMIC TARGET

TARGET: 90 wt. % In<sub>2</sub>O<sub>3</sub> / 10 wt. % SnO<sub>2</sub>

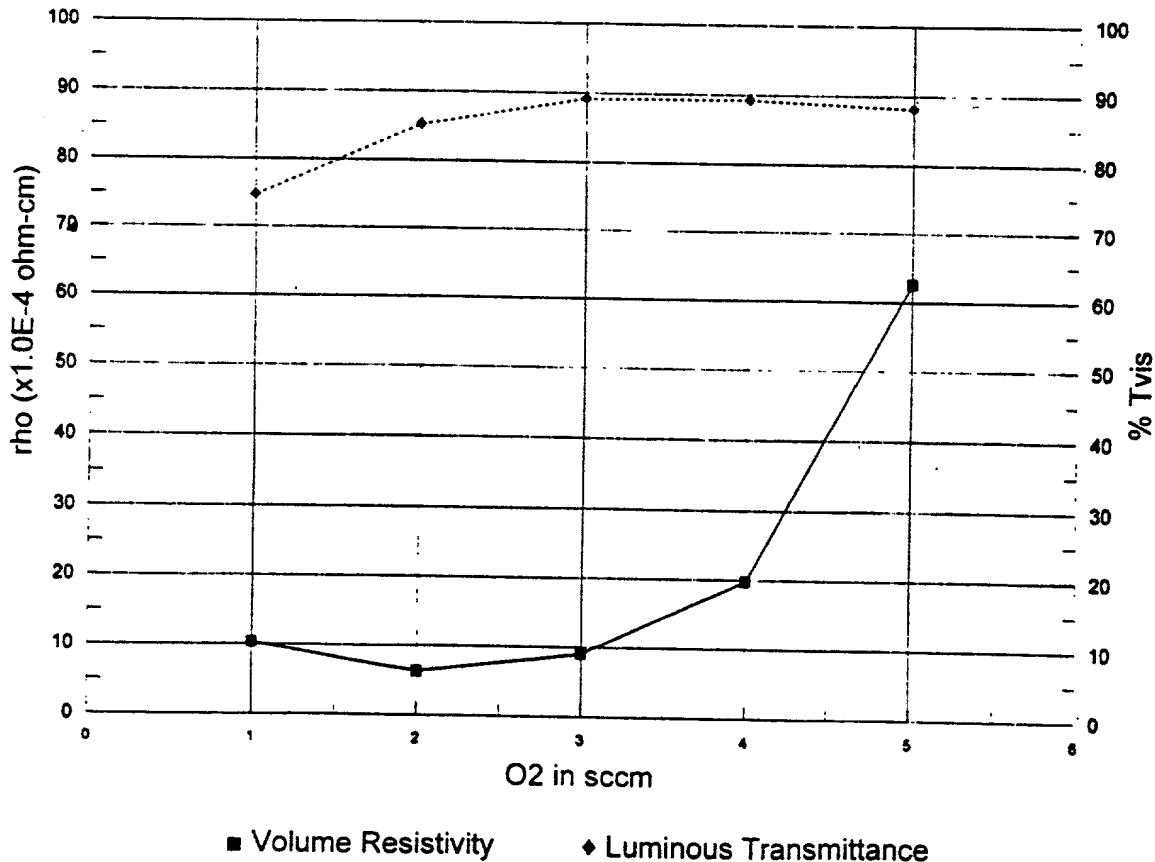
Date: 04-03-96

SUBSTRATE: Glass Slide

CONDITIONS: no heat  
power .50 KW  
speed 5.75 inch/min.  
total flow 50 sccm  
pressure 2.0 microns

O <sub>2</sub> (sccm)	1	2	3	4	5
R (ohms/square)	102	56.1	67	147.5	492
%T vis (Luminous)	74.7	85.3	89.2	89.3	88.2
thickness (nm, slide)	100.9	113.1	135.7	133.9	127.3
rho (x1.0E-4 ohm-cm)	10.3	6.3	9.1	19.8	62.6

RESISTIVITY WELL



# INDIUM TIN OXIDE CERAMIC TARGET

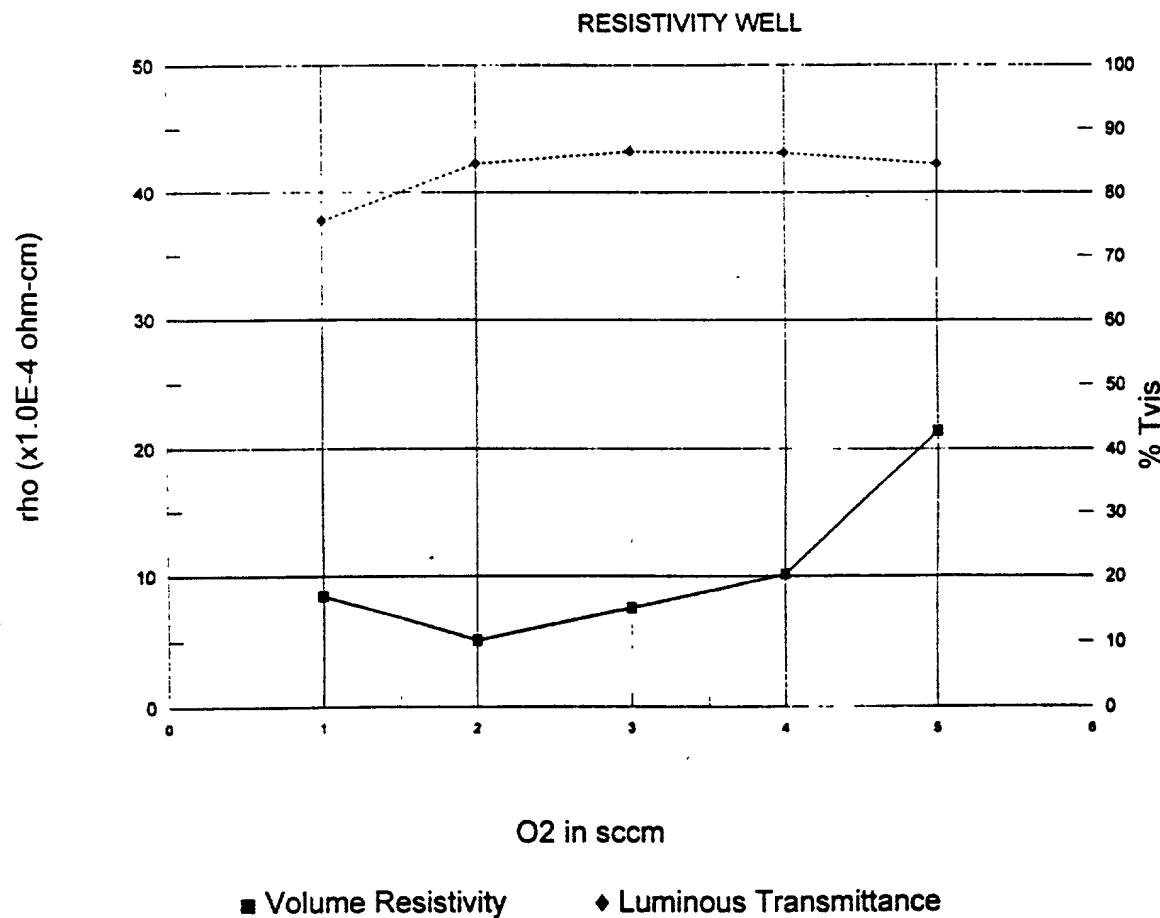
TARGET: 90 wt. % In<sub>2</sub>O<sub>3</sub> / 10 wt. % SnO<sub>2</sub>

Date: 04-03-96

SUBSTRATE: ICI 725 PET

CONDITIONS: no heat  
power .50 KW  
speed 5.75 inch/min.  
total flow 50 sccm  
pressure 2.0 microns

O <sub>2</sub> (sccm)	1	2	3	4	5
R (ohms/square)	83.9	45.2	55.6	75.7	168.3
%T vis (Luminous)	75.5	84.6	86.5	86.3	84.5
thickness (nm, slide)	100.9	113.1	135.8	133.9	127.3
rho (x1.0E-4 ohm-cm)	8.5	5.1	7.6	10.1	21.4



# INDIUM TIN OXIDE CERAMIC TARGET

TARGET: 90 wt. % In<sub>2</sub>O<sub>3</sub> / 10 wt. % SnO<sub>2</sub>

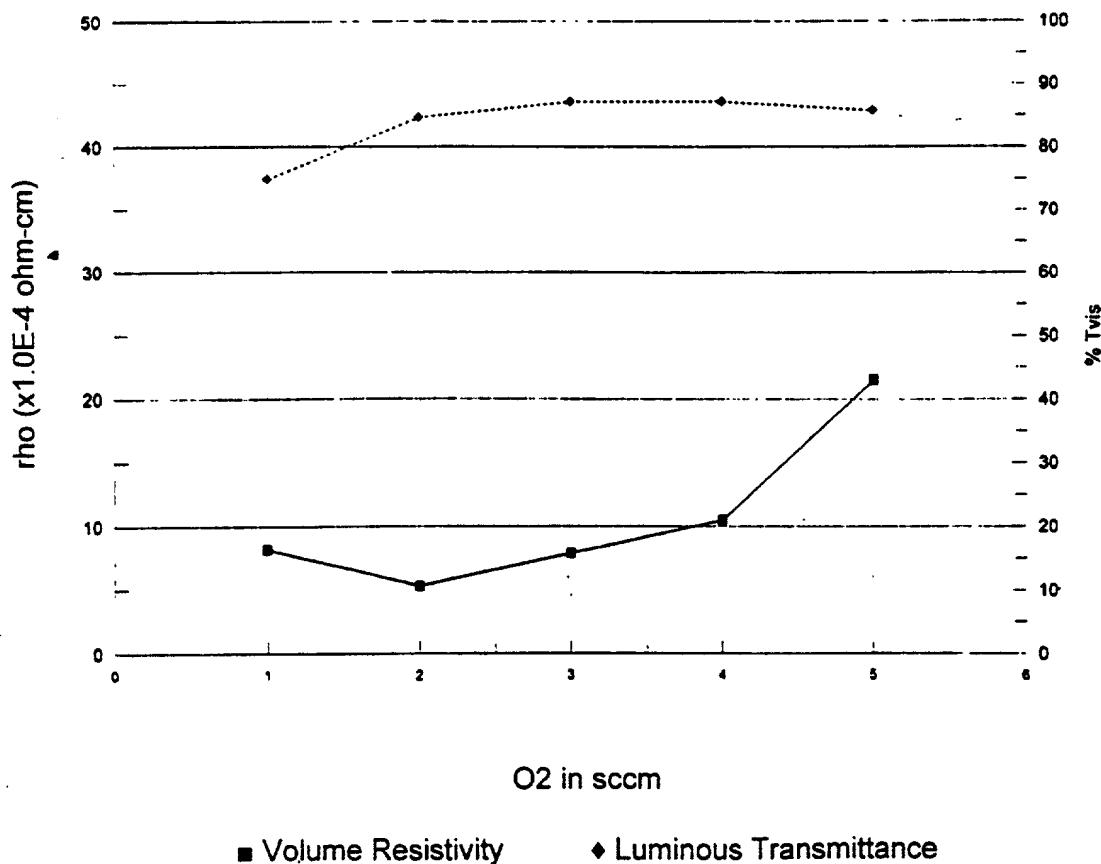
Date: 04-03-96

SUBSTRATE: Hardcoat PET

CONDITIONS: no heat  
power .50 KW  
speed 5.75 inch/min.  
total flow 50 sccm  
pressure 2.0 microns

O <sub>2</sub> (sccm)	1	2	3	4	5
R (ohms/square)	81.5	46.9	58.2	78.4	168.9
%T vis (Luminous)	74.9	84.7	87.2	87.2	85.8
thickness (nm, slide)	100.9	113.1	135.7	133.9	127.3
rho (x1.0E-4 ohm-cm)	8.2	5.3	7.9	10.5	21.5

RESISTIVITY WELL



# TIN OXIDE CERAMIC TARGET

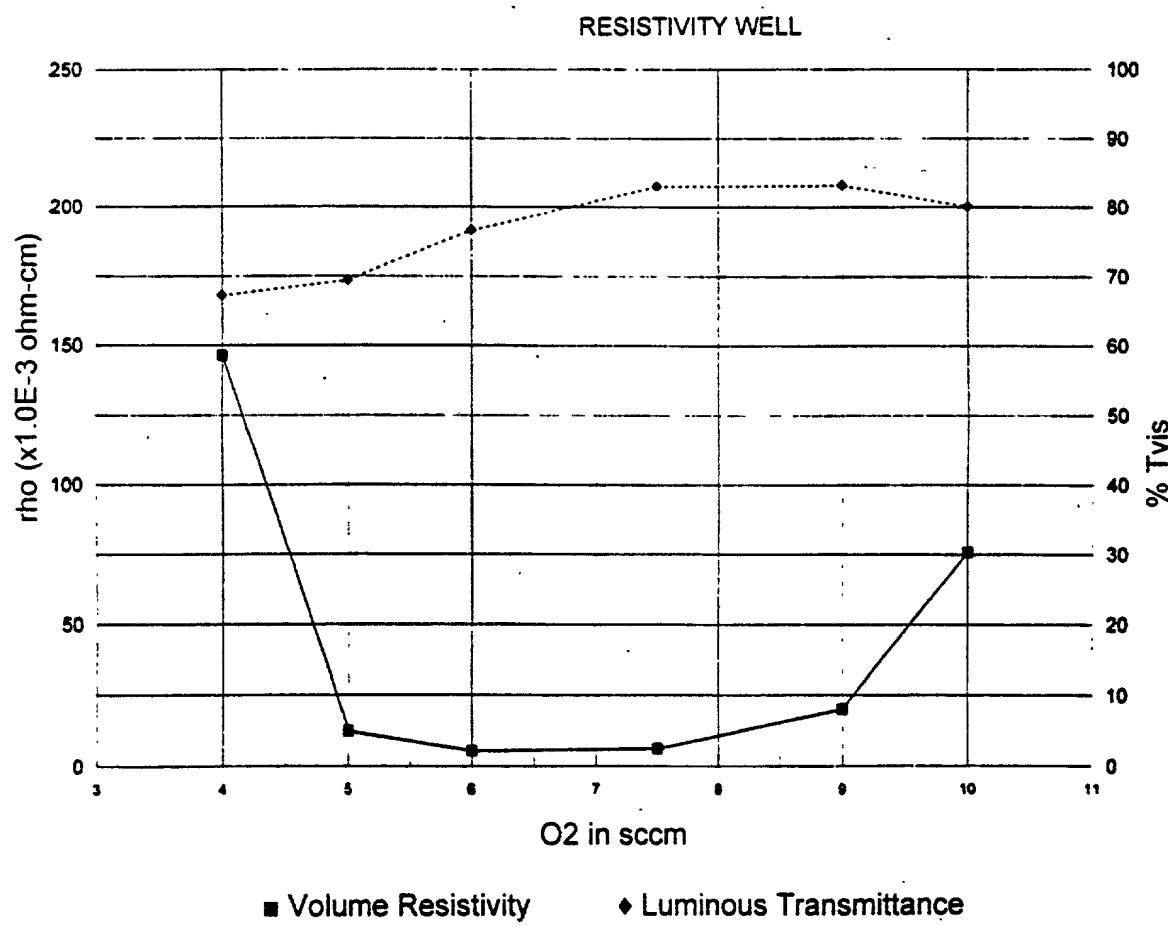
TARGET: 98 wt. % SnO<sub>2</sub> / 2 wt.% Sb203

Date: 04-09-96

SUBSTRATE: ICI 725 PET

CONDITIONS: no heat  
power .50 KW  
speed 5.75 inch/min.  
total flow 50 sccm  
pressure 1.8 – 1.9 microns

O2 (sccm)	4	5	6	7.5	9	10
R (ohms/square)	4710	420	183	214	714	3000
%T vis (Luminous)	67.2	69.4	76.6	83	83.2	80.1
thickness (nm, slide)	311	298.0	298.7	294.3	283.1	252.6
rho (x1.0E-3 ohm-cm)	146.5	12.5	5.5	6.3	20.2	75.8



# Zinc TIN OXIDE CERAMIC TARGET

TARGET: 98 wt. % ZnO / 2 wt.% Al<sub>2</sub>O<sub>3</sub>

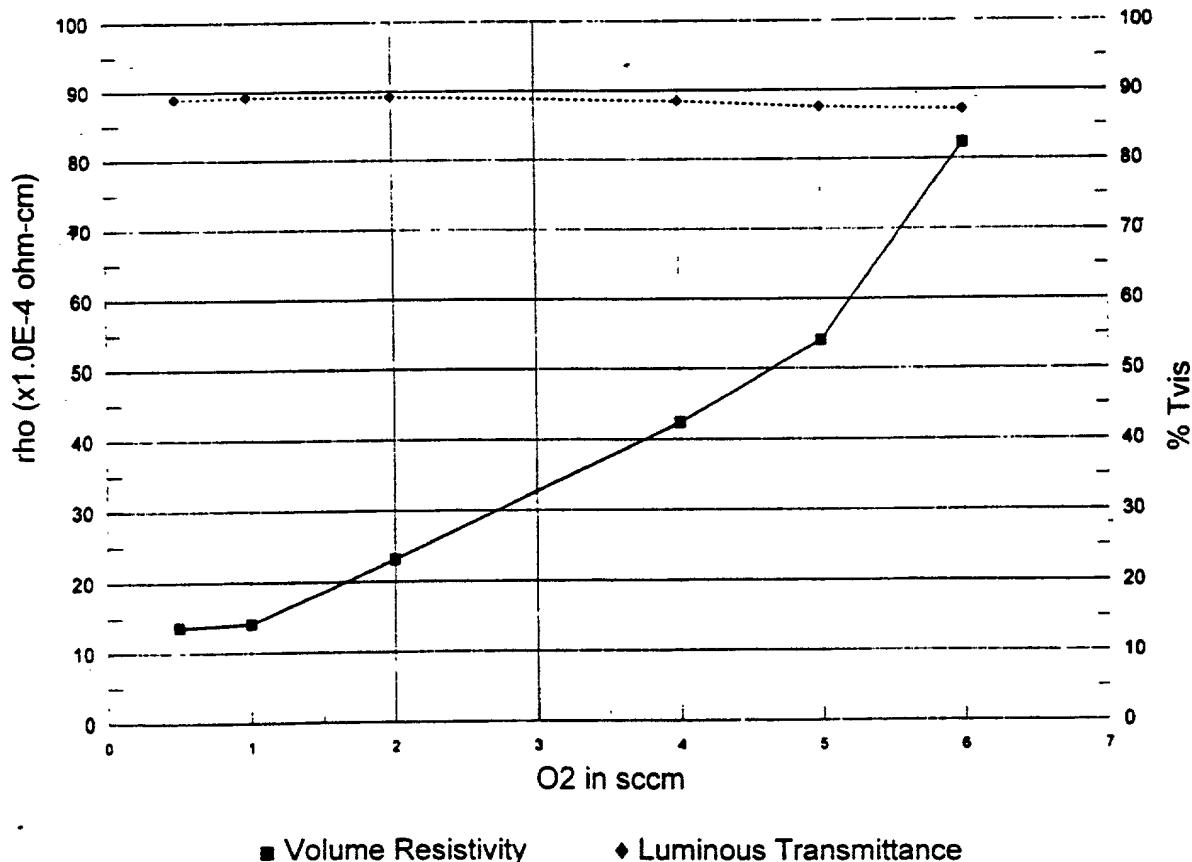
Date: 04-09-96

SUBSTRATE: ICI 725 PET

CONDITIONS: no heat  
power .50 KW  
speed 5.75 inch/min.  
total flow 50 sccm  
pressure 1.8 – 1.9 microns

O <sub>2</sub> (sccm)	0.5	1	2	4	5	6
R (ohms/square)	124.4	120.9	126.3	211	295	415
%T vis (Luminous)	88.9	89.2	89.2	88.4	87.5	87.1
thickness (nm, slide)	109.9	116.8	183.0	200.9	183.5	198.4
rho (x1.0E-4 ohm-cm)	13.7	14.1	23.1	42.4	54.1	82.3

RESISTIVITY WELL



## **DEVELOPING AN ITO PROCESS**

### **MINIMIZING ABSORPTION**

- CALCULATE SPECTRAL ABSORPTION COEFFICIENTS FROM MEASURED DATA ON RESISTIVITY "WELL" SAMPLES
- PLOT SPECTRAL ABSORPTION COEFFICIENTS VERSUS WAVELENGTH WITH OXYGEN FLOW RATE AS A PARAMETER
- FOR APPLICATIONS WHERE A SINGLE WAVELENGTH IS DOMINATE PLOT THAT ABSORPTION COEFFICIENT VERSUS FLOW RATE
- SELECT FLOW RATE FOR PROCESS WHICH MINIMIZES ABSORPTION COEFFICIENT NEAR RESISTIVITY MINIMUM

THE UNIVERSITY OF TORONTO LIBRARIES

# INDIUM TIN OXIDE CERAMIC TARGET

TARGET: 90 wt. % In<sub>2</sub>O<sub>3</sub> / 10 wt.% SnO<sub>2</sub>

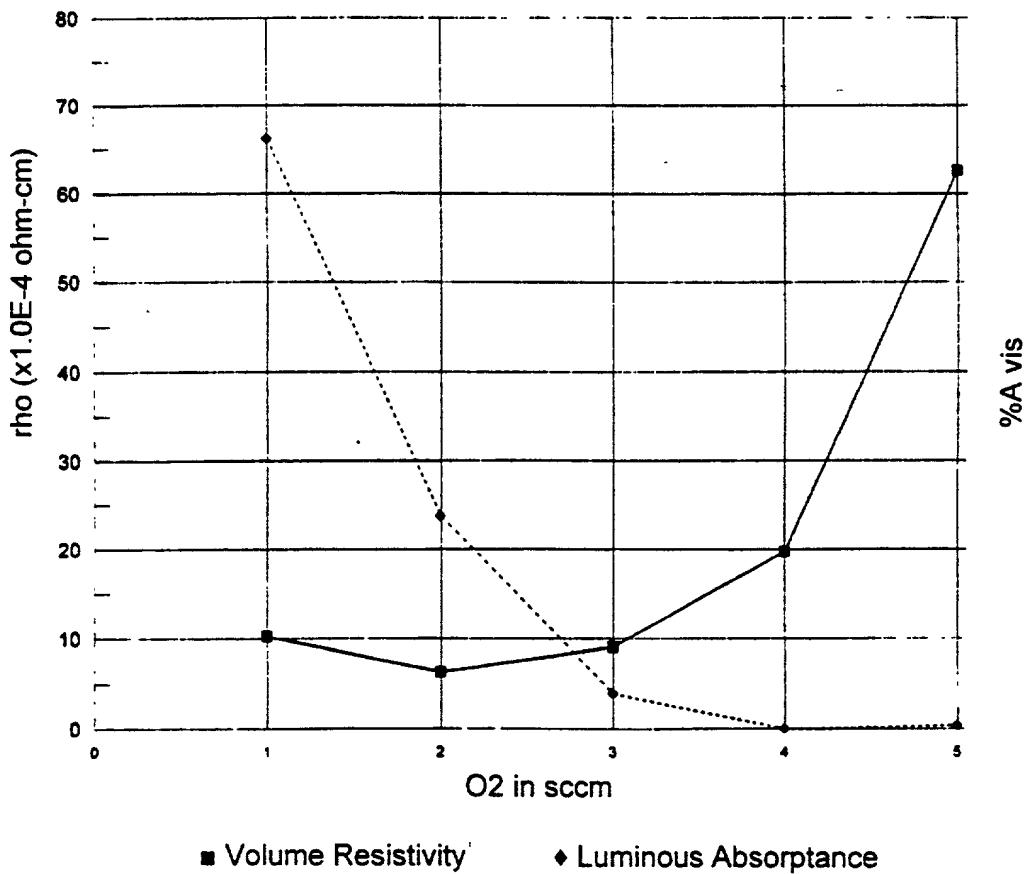
Date: 04-09-96

SUBSTRATE: Glass Slide

CONDITIONS: no heat  
power .50 KW  
speed 5.75 inch/min.  
total flow 50 sccm  
pressure 1.8 – 1.9 microns

O <sub>2</sub> (sccm)	1	2	3	4	5
R (ohms/square)	102	56.1	67	147.5	492
%T vis (Luminous)	74.7	85.3	89.2	89.3	88.2
thickness (nm, slide)	100.9	113.1	135.7	133.9	127.3
rho (x1.0E-4 ohm-cm)	10.3	6.3	9.1	19.8	62.6
%A vis (Luminous)	13.24	4.75	0.78	0	0.08

RESISTIVITY WELL



# INDIUM TIN OXIDE CERAMIC TARGET

TARGET: 90 wt. % In<sub>2</sub>O<sub>3</sub> / 10 wt.% SnO<sub>2</sub>

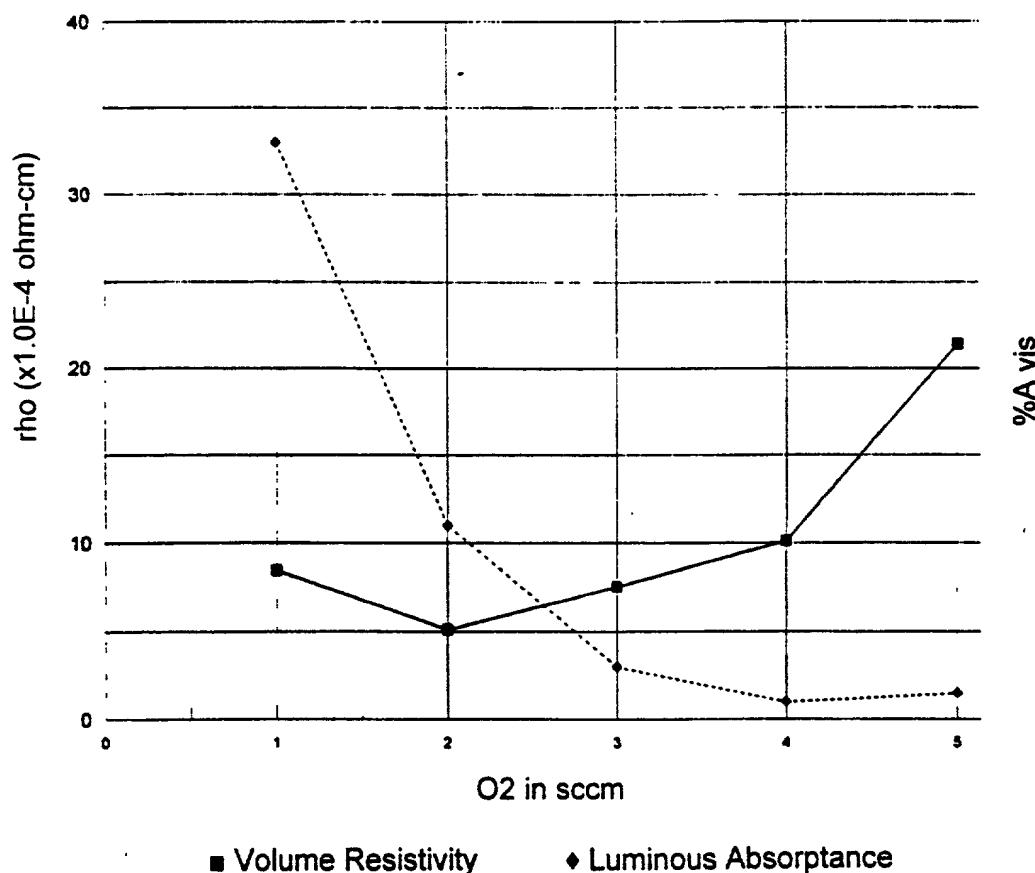
Date: 04-09-96

SUBSTRATE: ICI 725 PET

CONDITIONS: no heat  
power .50 KW  
speed 5.75 inch/min.  
total flow 50 sccm  
pressure 1.8 – 1.9 microns

O2 (sccm)	1	2	3	4	5
R (ohms/square)	83.9	45.2	55.6	75.7	168.3
%T vis (Luminous)	75.5	84.6	86.5	86.3	84.5
thickness (nm, slide)	100.9	113.1	135.8	133.9	127.3
rho (x1.0E-4 ohm-cm)	8.5	5.1	7.6	10.1	21.4
%A vis (Luminous)	13.2	4.4	1.2	0.4	0.6

## RESISTIVITY WELL



# INDIUM TIN OXIDE CERAMIC TARGET

TARGET: 90 wt. % In<sub>2</sub>O<sub>3</sub> / 10 wt.% SnO<sub>2</sub>

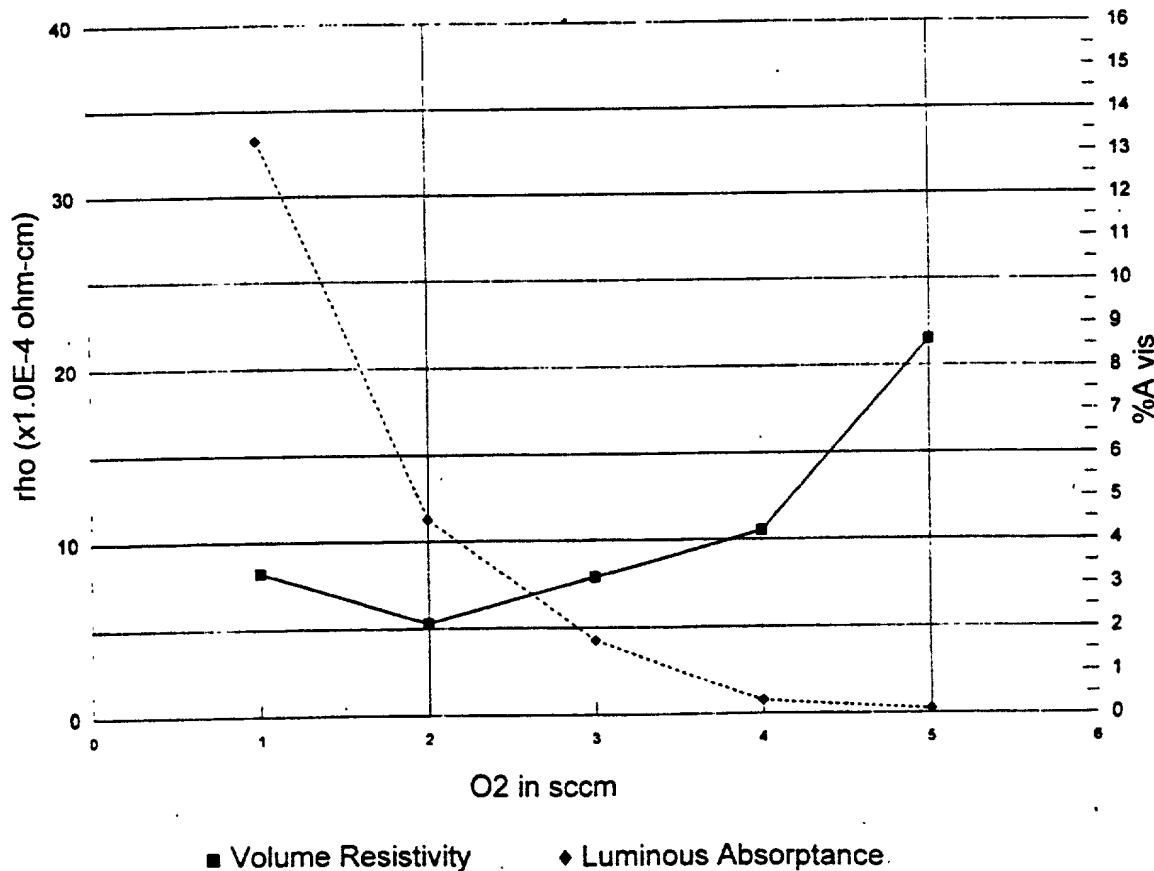
Date: 04-09-96

SUBSTRATE: Hardcoat PET

CONDITIONS: no heat  
power .50 KW  
speed 5.75 inch/min.  
total flow 50 sccm  
pressure 1.8 – 1.9 microns

O <sub>2</sub> (sccm)	1	2	3	4	5
R (ohms/square)	81.5	46.9	58.2	78.4	168.9
%T vis (Luminous)	74.9	84.7	87.2	87.2	85.8
thickness (nm, slide)	100.9	113.1	135.7	133.9	127.3
rho (x1.0E-4 ohm-cm)	8.2	5.3	7.9	10.5	21.5
%A vis (Luminous)	13.3	4.5	1.7	0.3	0.1

## RESISTIVITY WELL



## ITO PROCESS EXAMPLES

### DC MAGNETRON SPUTTERING

- REACTIVE PROCESS FROM 90% In / 10% Sn (WEIGHT) TARGET
- SUBSTRATE - PET (POLYETHYLENE TEREPHTHALATE) PLASTIC FILM
- TYPICAL ROLL COATER PROCESS PARAMETERS:
  1. CHAMBER PRESSURE - 3.7 MICRONS (3.7 MILLITORR)
  2. FLOW RATES 265 SCCM ARGON, 144 SCCM OXYGEN
  3. ITO THICKNESS NEAR 100 NM
  4. TARGET AREA =  $75 \text{ IN}^2 = 484 \text{ CM}^2$ , SO FOR TARGET POWER OF  
2000 WATTS POWER DENSITY =  $\frac{4.1 \text{ WATTS}}{\text{CM}^2}$
  5. DEPOSITION RATE =  $6.5 \frac{\text{NM}}{\text{SEC}}$
  6. SUBSTRATE TEMPERATURE - NEAR ROOM TEMPERATURE  
(COOLED DRUM)

## **ITO PROCESS EXAMPLES**

### **DC MAGNETRON SPUTTERING - REACTIVE PROCESS**

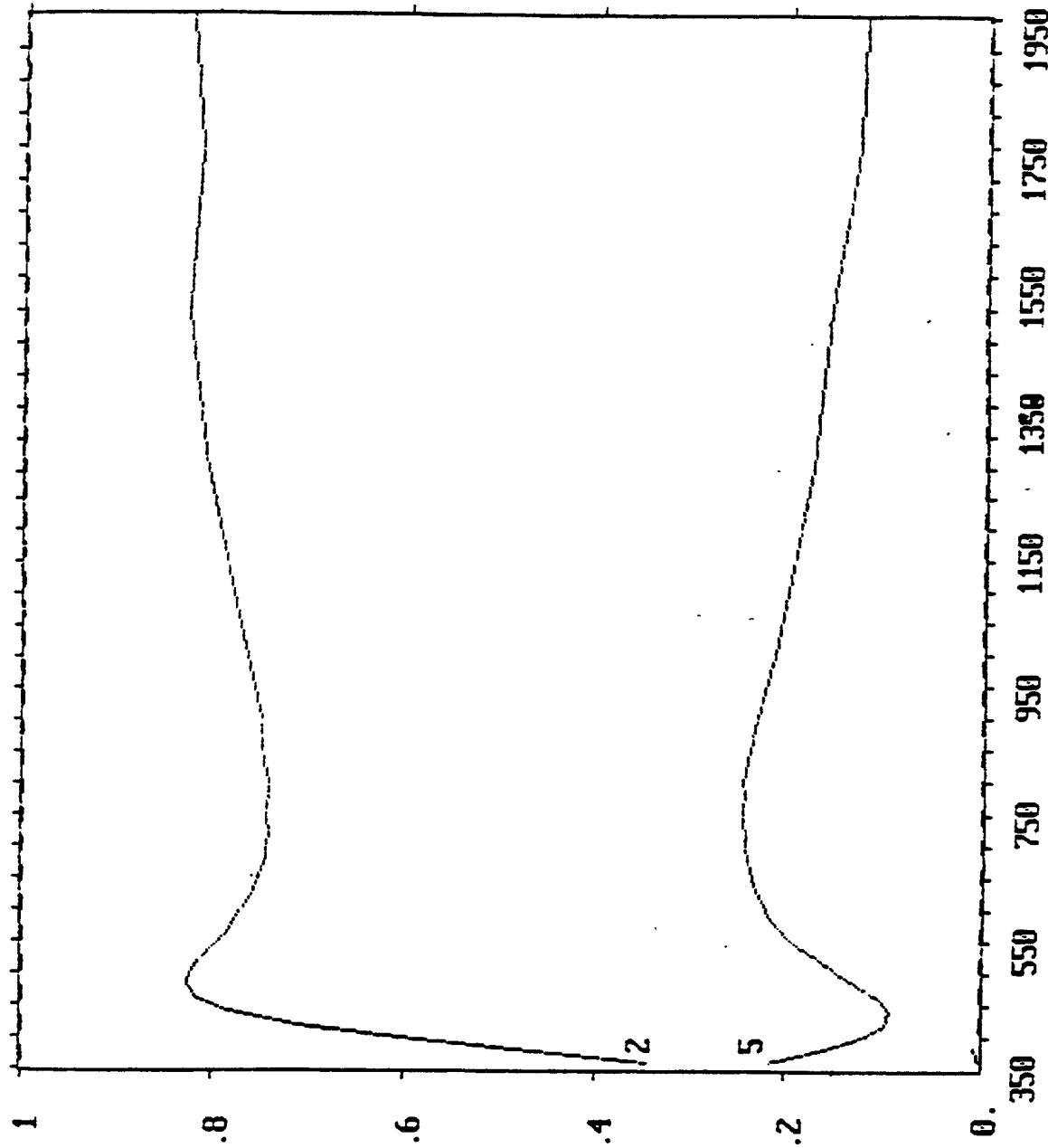
- RESISTIVITY VERSUS OXYGEN FLOW RATE WITH CORRESPONDING OPTICAL PROPERTIES:

<u>OHMS/SQUARE</u>	<u>O<sub>2</sub> RATE (SCCM)</u>	<u>LUMINOUS % T</u>	<u>LUMINOUS % R</u>
74	141	78.5	18.6
192	144	79.0	19.2
232	147	80.7	16.9
370	148	81.5	16.3
555	149	82.0	15.6
1428	150	83.4	14.4
2000	155	87.4	11.2

F 0 4 2 8 0 " 3 0 0 6 6 0

15.7

2 for Zoom SPECTRA VS WAVELENGTH PASS 1 GLOW METERS:



Tvi 79.0 TW@ 492. TW@ 0.  
Rvi 19.2 RW@ 438. RW@ 753.

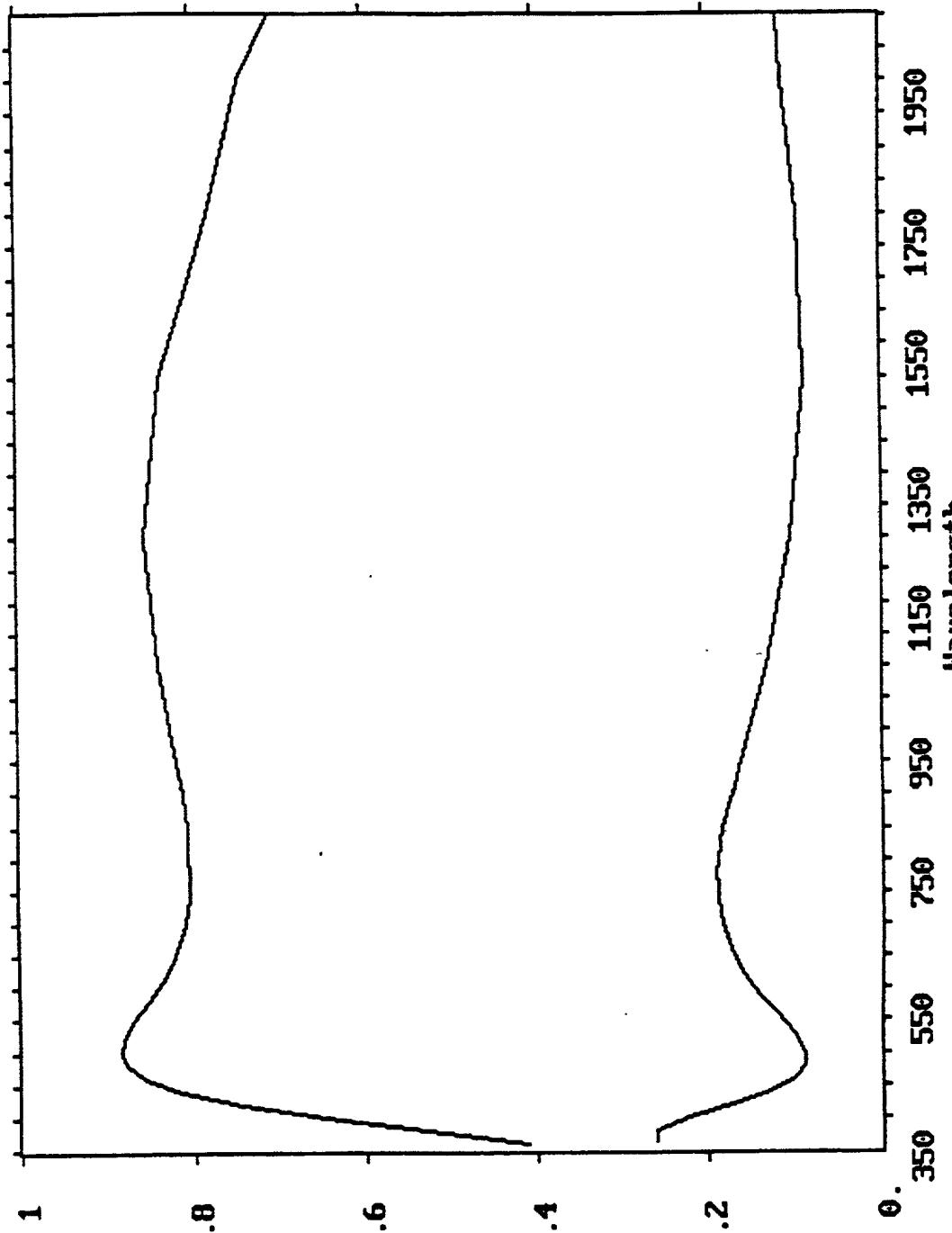
## **ITO PROCESS EXAMPLES**

### **DC MAGNETRON SPUTTERING**

- SEMIREACTIVE PROCESS FROM 90% In<sub>2</sub>O<sub>3</sub> / 10% SnO<sub>2</sub> (WEIGHT)  
CERAMIC TARGET
- SUBSTRATES - PET FILM AND GLASS SLIDES
- TYPICAL IN-LINE COATER PROCESS PARAMETERS:
  1. CHAMBER PRESSURE - 2 MICRON (2 MILLITORR)
  2. FLOW RATES - 45 - 49 SCCM ARGON 1 - 5 SCCM OXYGEN
  3. ITO THICKNESS NEAR 130 NM
  4. TARGET AREA = 48 IN<sup>2</sup> = 310 CM<sup>2</sup> SO FOR TARGET POWER OF  
500 WATTS POWER DENSITY = 1.6 WATTS  
CM<sup>2</sup>
  5. DEPOSITION RATE = 3 NM  
SEC
  6. SUBSTRATE TEMPERATURE - NEAR ROOM TEMPERATURE

YODHE 230 " 20015 E 650

Set: 5 : File: B: /OPTICAL/DTA2.QPE : ITO/90/10/PET/02/BHT/55.6/OHMS/SQ/1358A/T



Zoom Hplot

3

## IO PROCESS EXAMPLE

### THERMAL EVAPORATION

- REACTIVE PROCESS FROM In METAL
- SUBSTRATES - GLASS AND OTHER TEMPERATURE TOLERANT MATERIALS
- TYPICAL BELL JAR COATER PROCESS PARAMETERS:
  1. CHAMBER PRESSURE - 1 TO 3 MILLITORR
  2. FLOW RATE - MAINTAIN OXYGEN PRESSURE
  3. IO THICKNESS - 100 NM TO 143 NM
  4. RATE - 0.1  $\frac{\text{NM}}{\text{SEC}}$
  5. SUBSTRATE TEMPERATURE - 230 °C

## IO PROCESS EXAMPLE

### THERMAL EVAPORATION

#### ■ RESISTIVITY VERSUS OXYGEN PRESSURE:

<u>OHMS/SQUARE</u>	<u>THICKNESS (NM)</u>	<u>RHO (MILLIOHMS-CM)</u>	<u>O<sub>2</sub> PRESSURE (MILLITORR)</u>
27.0	142.0	0.38	1.0
32.8	105.0	0.34	2.0
54.8	99.7	0.55	3.0

## 10 PROCESS EXAMPLE

### THERMAL EVAPORATION

#### ■ OPTICAL PERFORMANCE:

LUMINOUS TRANSMITTANCE  
LUMINOUS REFLECTANCE  
LUMINOUS ABSORPTANCE  
(AND SCATTERING)  
REFRACTIVE INDEX AT 550 NM  
EXTINCTION COEFFICIENT AT 550 NM

$$\begin{aligned} &= 88.1\% \\ &= 8.8\% \\ &= 3.1\% \end{aligned}$$

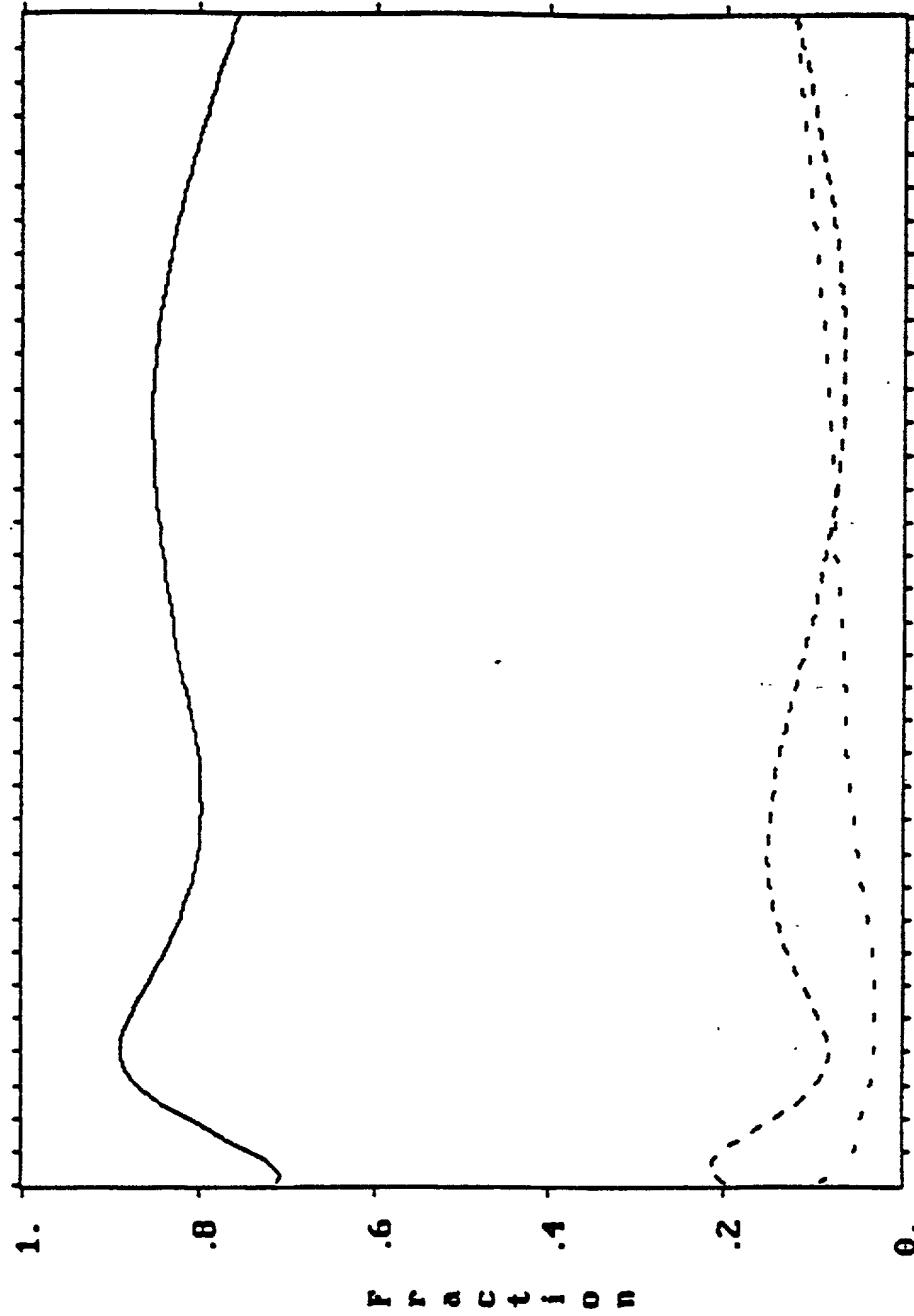
$$\begin{aligned} &= 1.91 \\ &= 8.2 \times 10^{-3} \end{aligned}$$

#### ■ ELECTRICAL PERFORMANCE:

SURFACE RESISTIVITY  
THICKNESS  
RESISTIVITY  
ELECTRON DENSITY  
MOBILITY

$$\begin{aligned} &= 27.0 \text{ OHMS/SQUARE} \\ &= 142.3 \text{ NM} \\ &= 3.8 \times 10^{-4} \text{ OHMS - CM} \\ &= 9.2 \times 10^{20} \text{ CM}^{-3} \\ &= 18 \frac{\text{CM}^2}{\text{VOLT SEC}} \end{aligned}$$

## IO PROCESS EXAMPLE



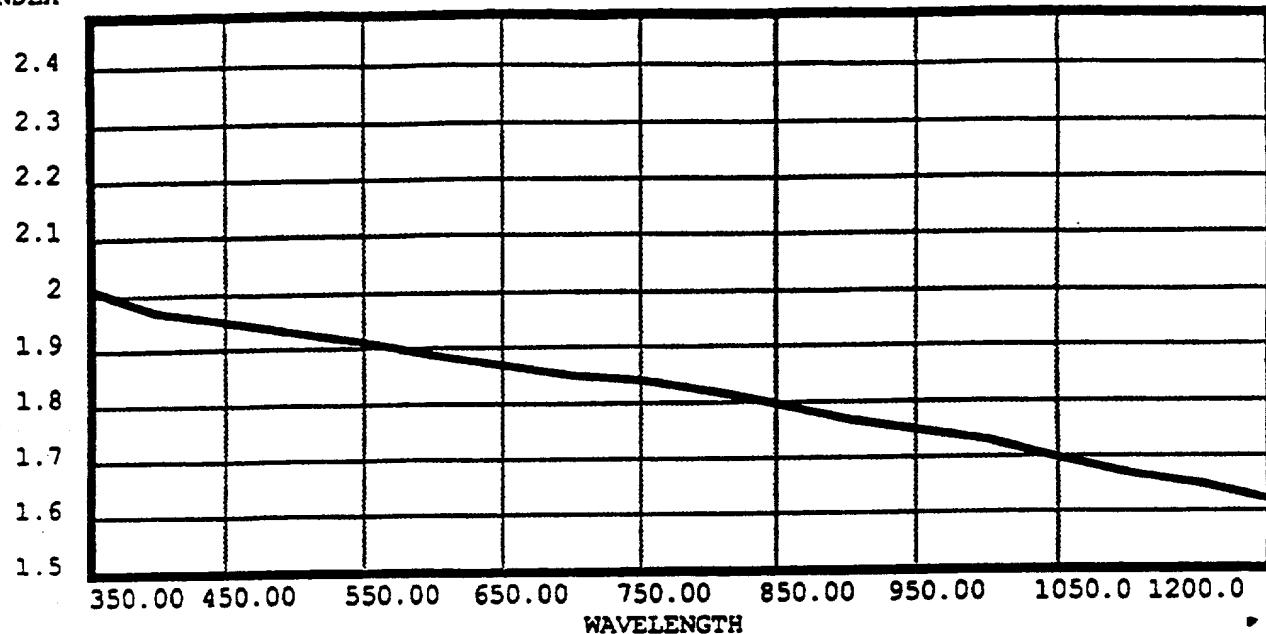
z for zoom  
Tvis=.881 Rvis=.088 Tsol=.833 Rsol=.119 Emis=.291  
T Dwell 567. R Dwell 566. m Pure 4.0 R Pure -21.6

## Thermal Evaporated Indium Oxide Coating on Glass, 27 Ohms/Square

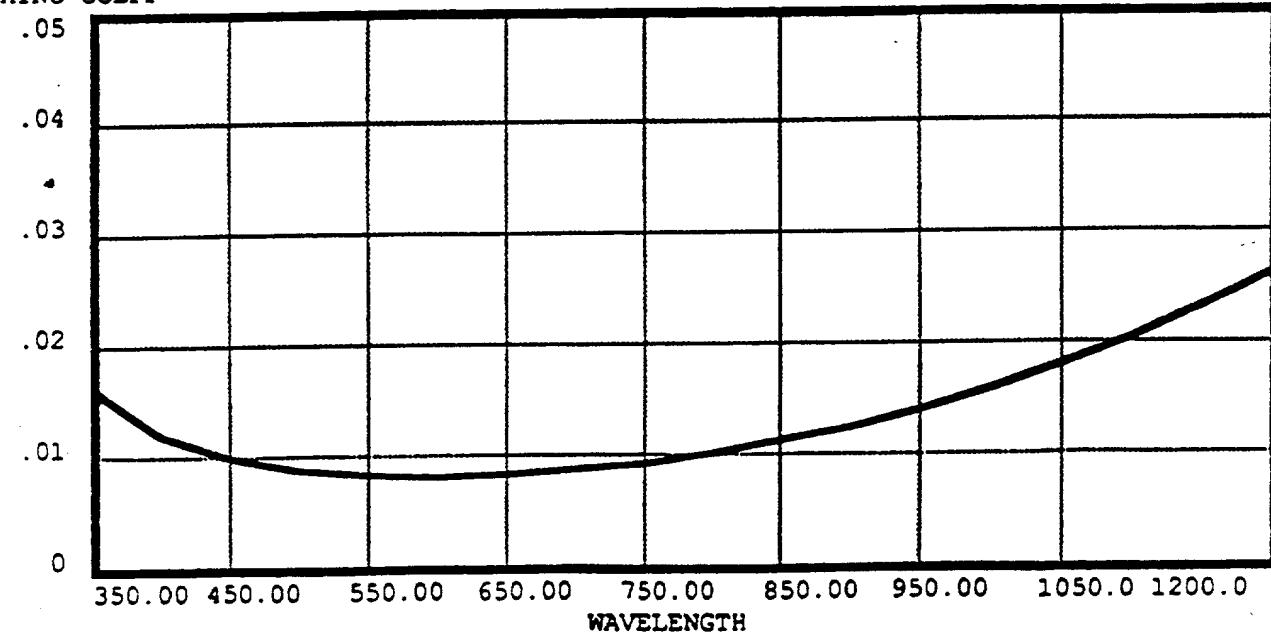
Transmittance – upper trace, Reflectance – middle trace, Absorptance – lower trace

## IO PROCESS EXAMPLE

INDEX



EXTNC COEFF



Optical Constant for Evaporated Indium Oxide Coating on Glass 1  
mtorr O<sub>2</sub>, 27 Ohms/Square  
(From C. I. Bright, 36<sup>th</sup> SVC Tech. Con. Proc., (1993) 63 – 67)

## ZrN PROCESS EXAMPLE

### DC MAGNETRON SPUTTERING

- REACTIVE PROCESS FROM Zr METAL TARGET
- SUBSTRATE-CORNING 7059 GLASS AND SILICON WAFERS
- TYPICAL IN-LINE COATER PROCESS PARAMETERS

1. CHAMBER PRESSURE = 0.2 – 0.3 Pa
2. FLOW RATES = 100 sccm ARGON, 15 – 25 sccm NITROGEN
3. ZrN THICKNESS ~ 18 – 390 nm
4. TARGET POWER = 1400 - 2400 WATTS
5. TARGET/SUBSTRATE DISTANCE = 120 mm
6. DEPOSITION RATE = 6 nm/sec
7. SUBSTRATE TEMPERATURE = 150 °C, 300 °C

(Data from M Veszelei et al, Optical Constants and Drude Analysis of Sputtered ZrN Films, Applied Optics, 33,10 1994)

## ZrN PROCESS EXAMPLE

### DC MAGNETRON SPUTTERING

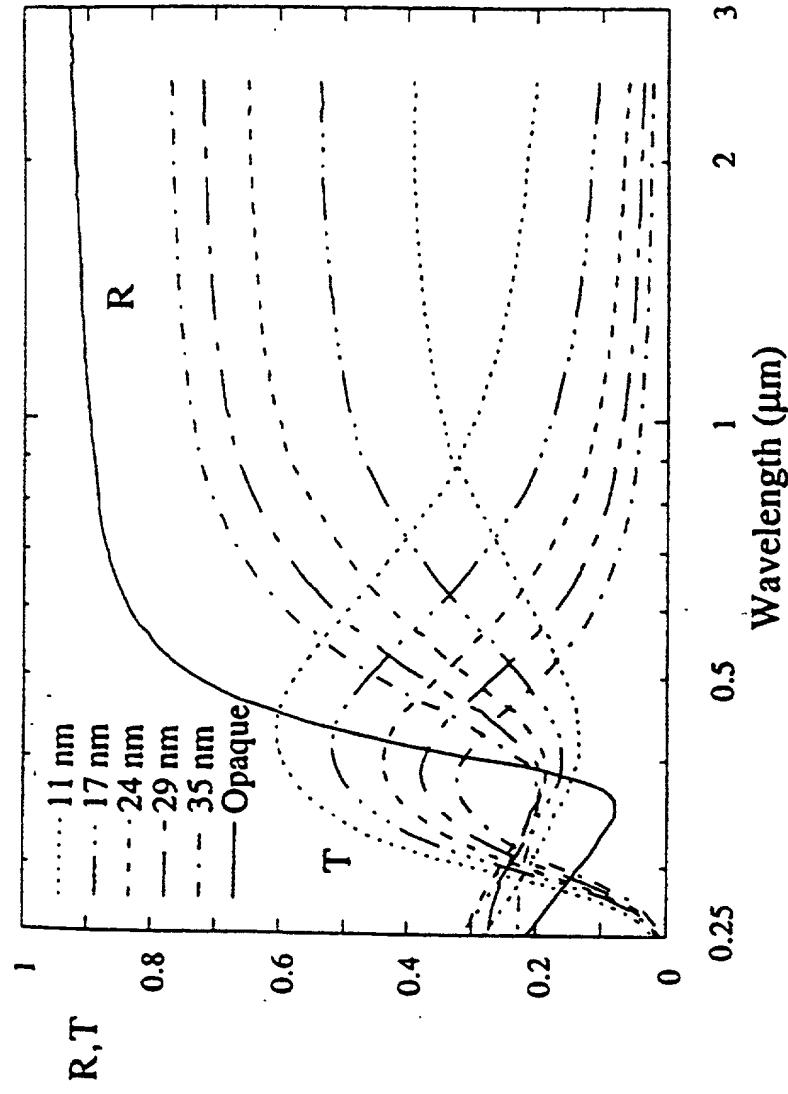
- REFLECTANCE AS A FUNCTION OF NITROGEN FLOW RATE

<u>N<sub>2</sub> FLOW RATE (SCCM)</u>	<u>REFLECTANCE (%) MINIMUM</u>	<u>REFLECTANCE (%) AT 2 um</u>	<u>REFLECTANCE (%) AT 10 um</u>
15	18% (305 nm)	77%	86%
*18	*15% (~420 nm)	*86%	*93%
20	8% (355 nm)	91%	94%
25	9% (355 nm)	90%	94%

(Data From M. Veszelei et al, A.O., 33 10, 1994 and \*Data From A. Spencer et al,  
Solar Energy Material, 18,1988)

## ZrN PROCESS EXAMPLE

### DC MAGNETRON SPUTTERING



Reflectance and Transmittance for Various Thickness of ZrN Films.  
(From M. Veszelei et al, Optical Characterization of Sputtered Semi-Transparent ZrN Films,  
Optical Materials 2, 1993)

## TiN PROCESS EXAMPLE

### RF MAGNETRON SPUTTERING

- REACTIVE PROCESS FROM Ti METAL TARGET
  - SUBSTRATE-CORNING 7059 BOROSILICATE GLASS
  - R&D COATER
8. CHAMBER PRESSURE = 0.67 Pa
  9. GAS MIXTURE = ARGON WITH 8% NITROGEN
  10. THICKNESSES = 4 - 76 nm
  11. TARGET POWER = 100 WATTS
  12. DEPOSITION RATE = 10.6 nm/min
  13. SUBSTRATE TEMPERATURE = 400 °C

(Data from M. Kawamura et al, Characterization of Thin, Transparent and Conductive TiN Films, JVST A, 16 (1) 1998)

## TiN PROCESS EXAMPLE

### RF MAGNETRON SPUTTERING

- ELECTRICAL AND OPTICAL PROPERTIES OF TiN THIN FILMS

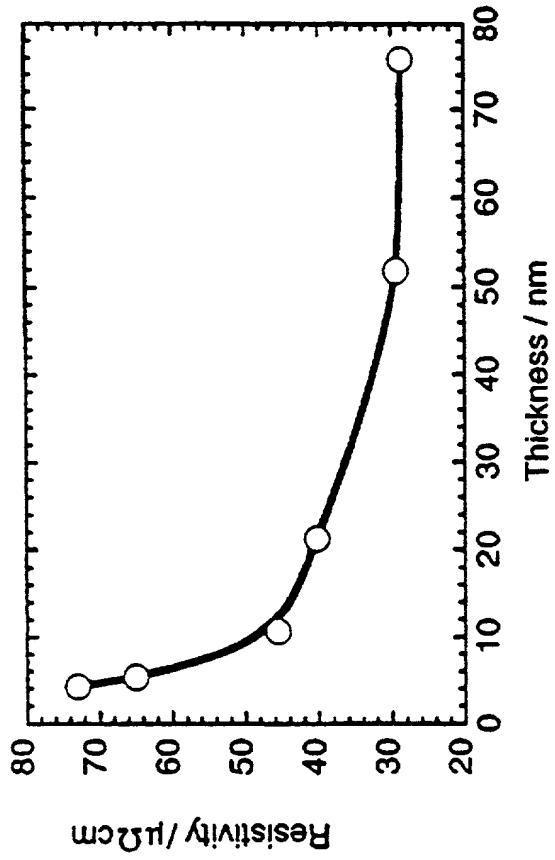
Thickness (nm)	Sheet resistance ( $\Omega/\square$ )	Resistivity ( $\mu\Omega \text{ cm}$ )	T <sub>max</sub> (%)
4.2	173	73	79
5.3	123	65	76
11	43	46	64
21	19	40	47
52	5.7	30	26

(From M. Kawamura et al, Characterization of TiN Films, JVST A 16 (1) 1998)

## TiN PROCESS EXAMPLE

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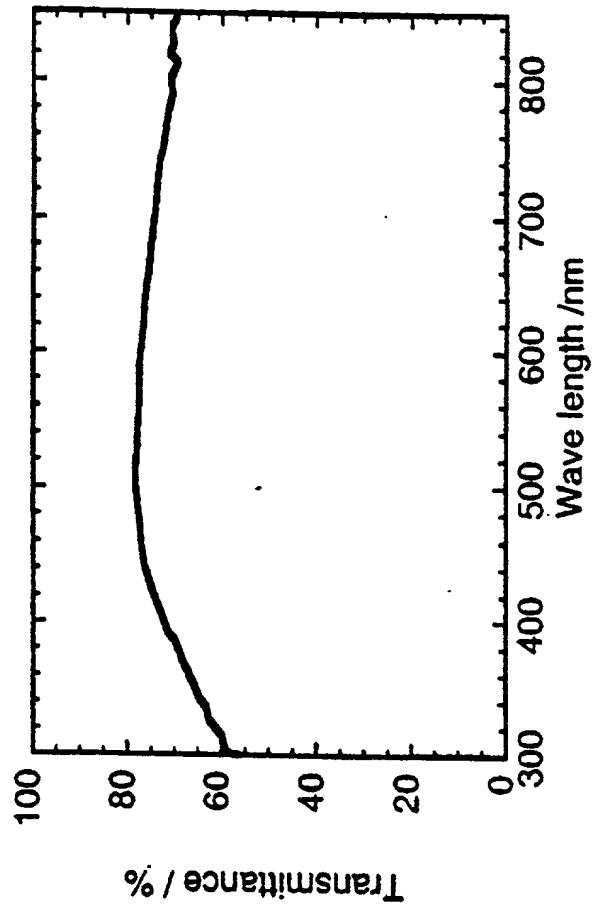
### RF MAGNETRON SPUTTERING



The Resistivity ( $\rho$ ) Change With Film Thickness of TiN Films.  
(From M. Kawamura et al, Characterization of TiN Films, JVST A 16 (1) 1998)

## TiN PROCESS EXAMPLE

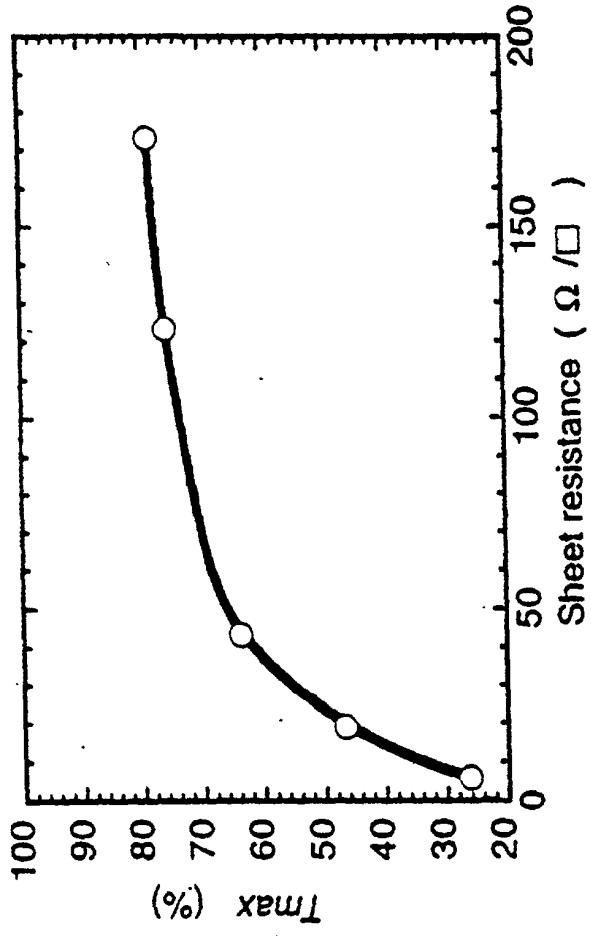
### RF MAGNETRON SPUTTERING



Transmission of TiN Film ( $d=4.2\text{ nm}$ ) (Glass Substrate Removed).  
(From M. Kawamura et al, characterization of TiN Films, JVST A 16 (1) 1998)

## TiN PROCESS EXAMPLE

### RF MAGNETRON SPUTTERING



Relationship Between Sheet Resistance and Maximum Transmission  
(at ~500 nm) of TiN Films.  
(From M. Kawamura et al, Characterization of TiN Films, JVST A 16(1) 1998)

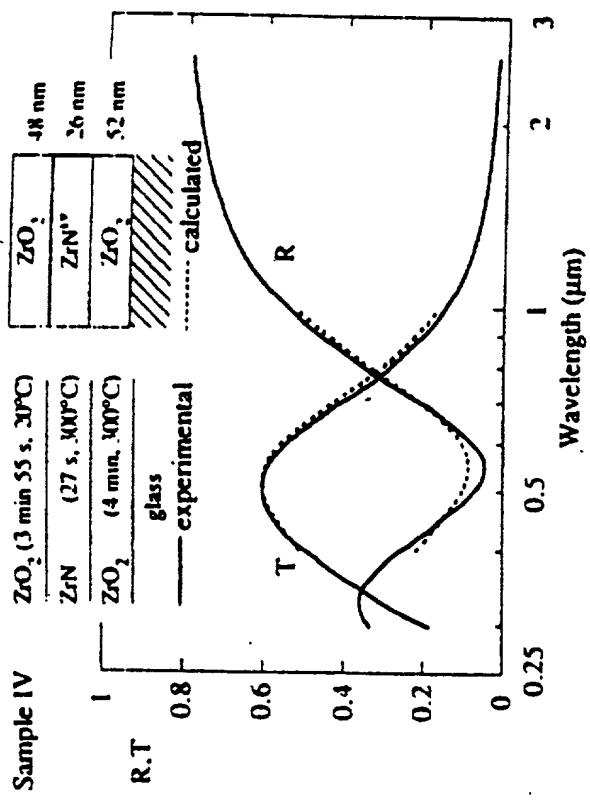
## KEY COATING PARAMETERS BY APPLICATION FUNCTION

Parameter	Transparent Electrodes	EMI Shield	Heater	Antistatic	Heat Mirror	AR
Resistance (Ohms)	X		X			
Surface Resistivity (Ohms/Square)	X	X				
Visible Transmittance	X	X	X	X	X	X
Visible Reflectance						
Infrared Reflectance						X

## APPLICATION EXAMPLES

### HEAT MIRROR

#### ■ OPTICALLY ENHANCED ZrN

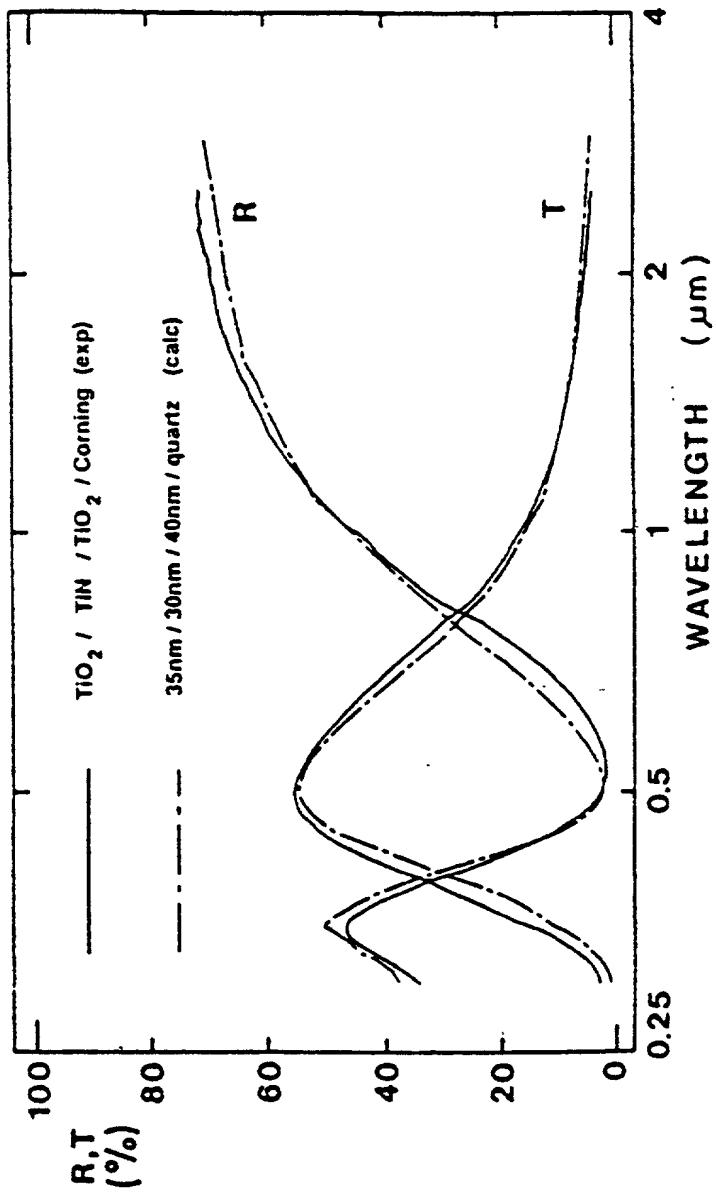


Calculated and Measured Reflectance and Transmittance for  $\text{ZrO}_2/\text{ZrN}/\text{ZrO}_2$ .  
 (From K. Andersson et al, ZrN Based Transparent Heat Mirror Coatings, Solar Energy Mat. 32, 1994)

## APPLICATION EXAMPLES

### HEAT MIRROR

#### ■ OPTICALLY ENHANCED TiN



Calculated and Measured Reflectance and Transmittance for  $\text{TiO}_2/\text{TiN}/\text{TiO}_2$ .  
(From Y. Claesson et al, Characterization of TiN-Based Solar Control Coatings, Solar Energy Mat. 20, 1990)

## MATCHING APPLICATION REQUIREMENTS

### RESISTIVITY ANTI - ICING HEATER FOR TV AND LASER WINDOW

#### REQUIREMENTS

- Power Dissipation Of 1.5 Watts/in<sup>2</sup> From 28 Volt Source
- Coated Window Transmittance of
  - T visible > 84% From 525 nm 625 nm
  - T average > 83% Between 700 nm 900 nm
  - T laser > 82% At 1070nm
- Laser Damage Resistant
- Durability to MIL-C-48497

## MATCHING APPLICATION REQUIREMENTS

- APPLICATION TYPE: Resistive Heater
- TRADEOFF PRIORITIES:
  1. Electrical Performance (resistance)
  2. Optical Performance
  3. Laser Damage Resistance
  4. Durability
  5. Cost

## MATCHING APPLICATION REQUIREMENTS

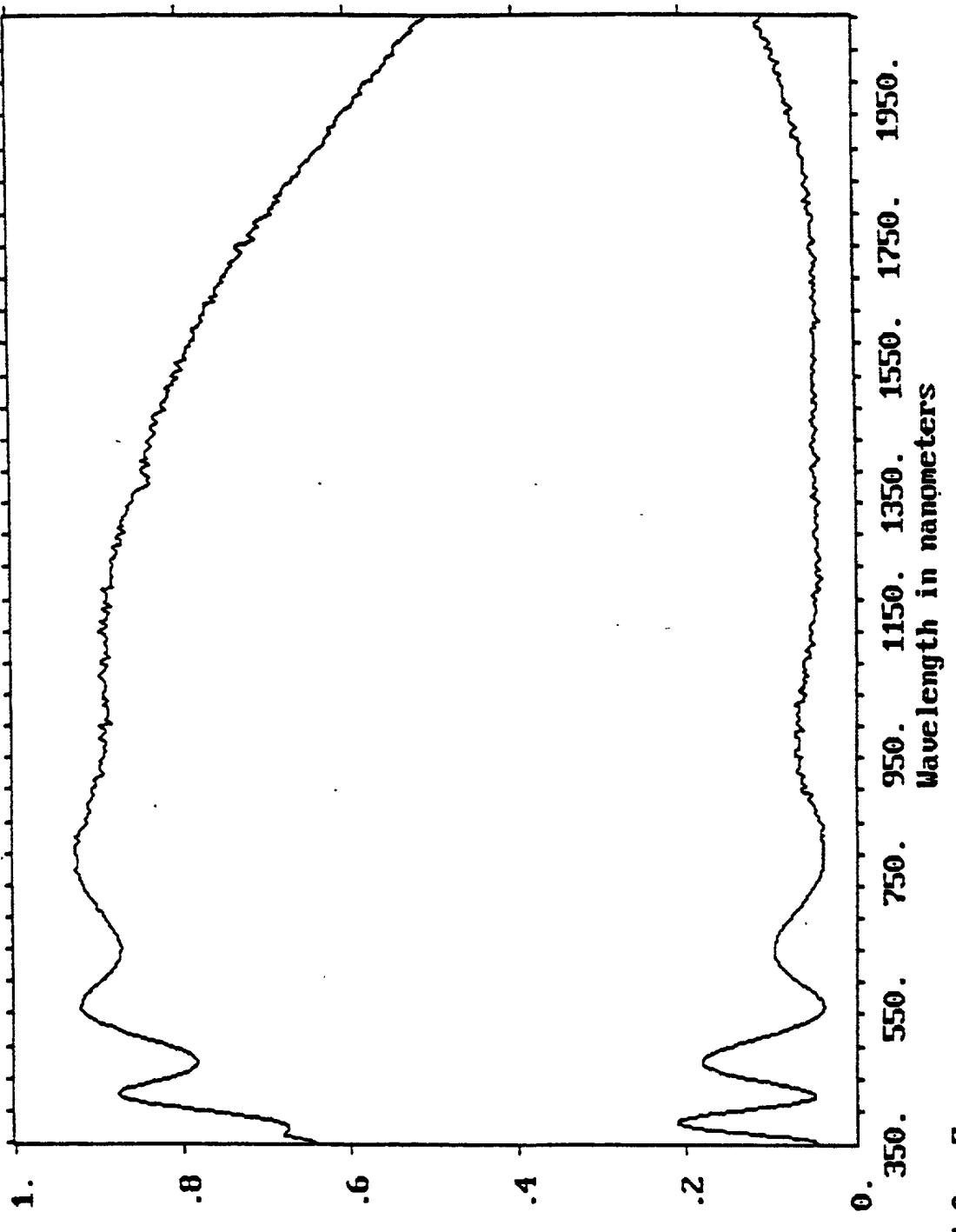
- Coating Surface Resistivities Between 10.6 And 14.2 Ohms/Square Yields Correct Resistance For Proper Heating
- Two Layer ITO/SiO<sub>2</sub> Coating Design Meets Optical Requirements
- Design Adjusted For Electric Field Control At Interfaces
- Durability Met By Materials Choice And Deposition Process

## MATCHING APPLICATION REQUIREMENTS

### MEASURED TCO PERFORMANCE

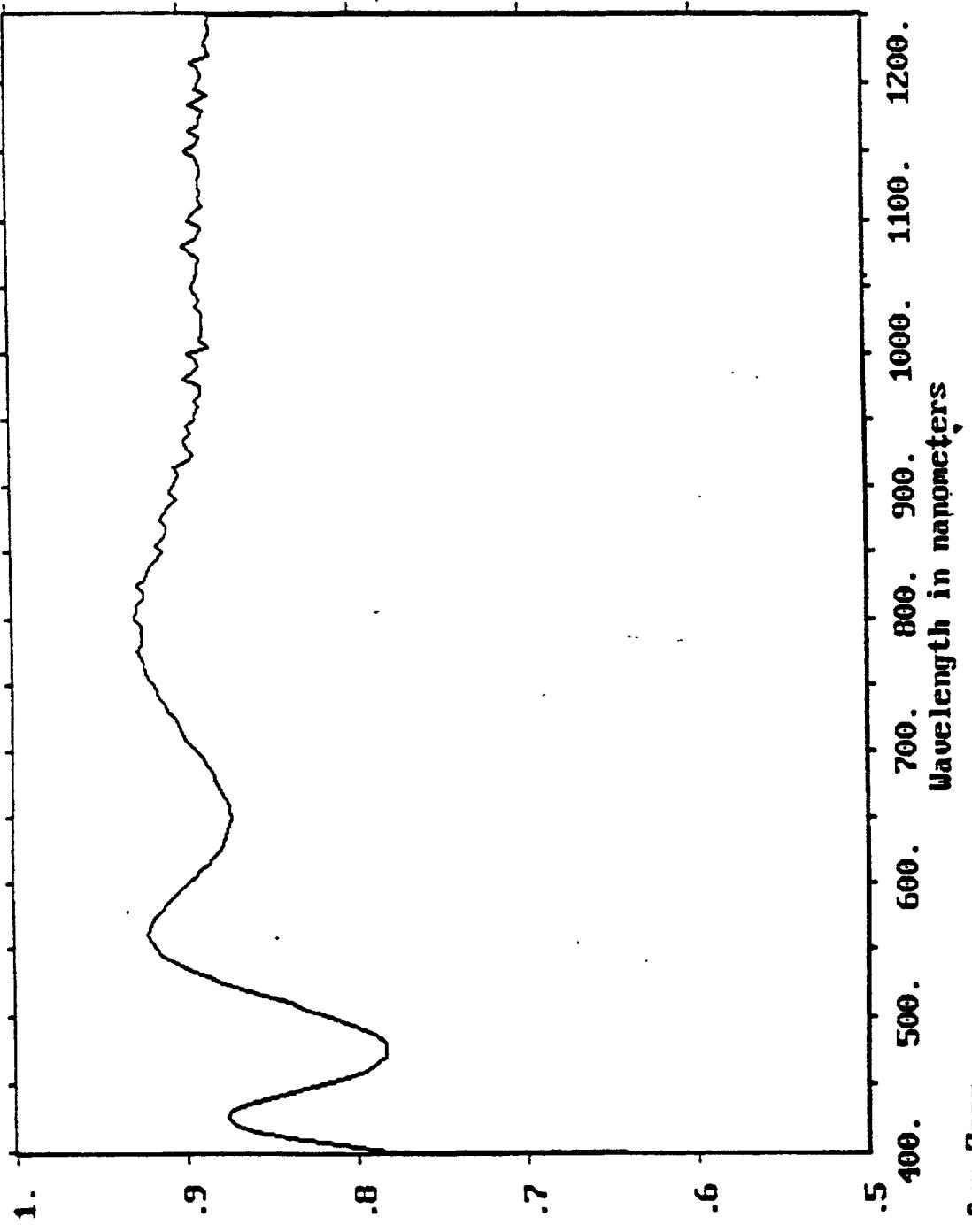
- Heater Resistance = 7.9 Ohms (11.3 OHMs/Square)
- Window Transmittance
  - T visible 525nm - 625nm = 88%
  - T average 700nm - 910nm = 92%
  - T laser 1070nm = 89%
- Passed Laser Damage Testing At 22.5 to 36.0 MW/cm<sup>2</sup>
- Passed Durability Tests Of MIL-C-48497

RESISTIVITY ANTI-ICING HEATER FOR TV AND LASER WINDOW



100 200 300 400 500 600 700 800 900 1000 1100 1200

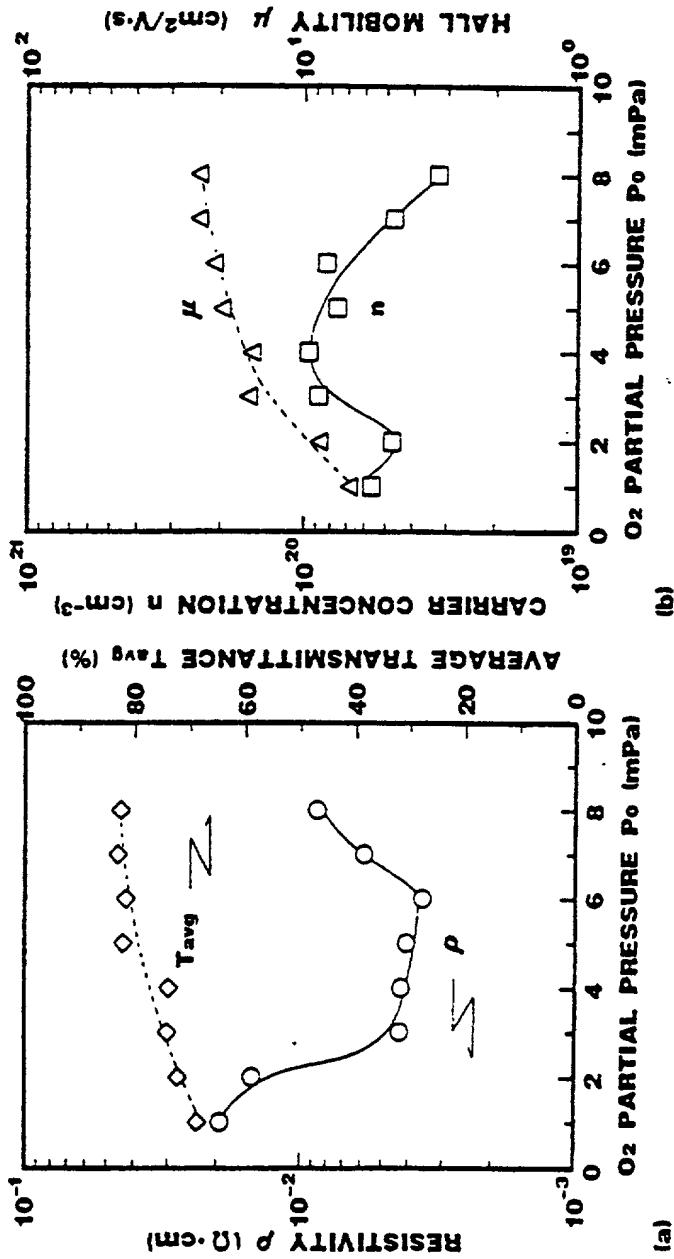
### RESISTIVITY ANTI-ICING HEATER FOR TV AND LASER WINDOW



Z for zoom

## ADVANCED TOPICS

### NEW TCO MATERIALS

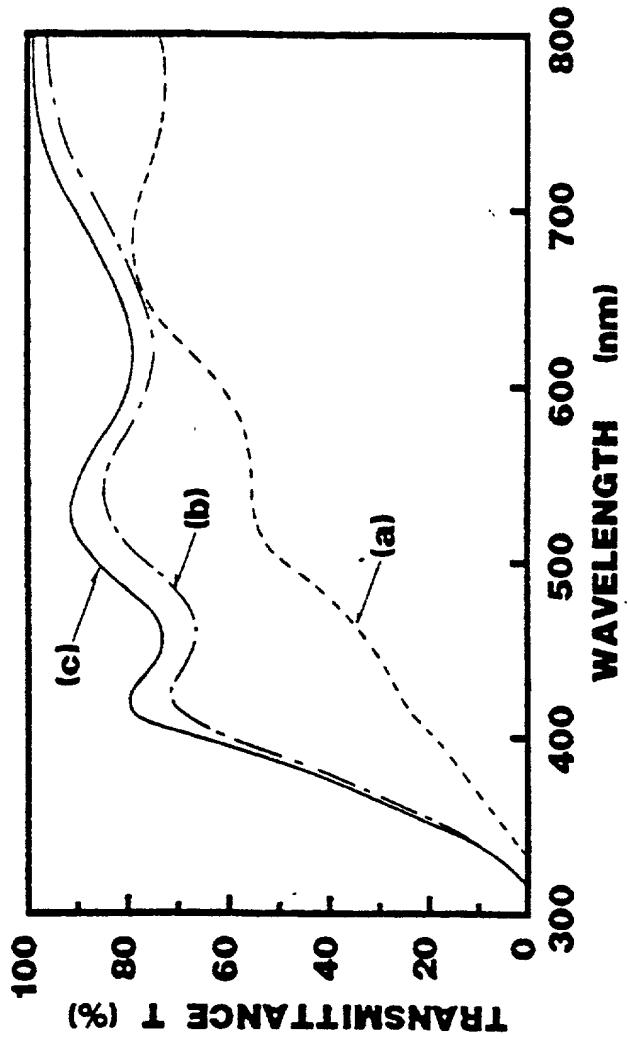


(a) Resistivity (o) and Average Transmittance in the Visible Range (◊), (b) Hall Mobility ( $\Delta$ ) and Carrier Concentration ( $\square$ ) as Functions of the Oxygen Partial Pressure for Zinc Stannate Films Prepared at RT ( $\sim 140^\circ\text{C}$ ).  
(From T. Minami et al, Preparation of Transparent Zinc Stannate Conducting Films, JVST A, 13, 3 1995)

ADVANCED TOPICS

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NEW TCO MATERIALS

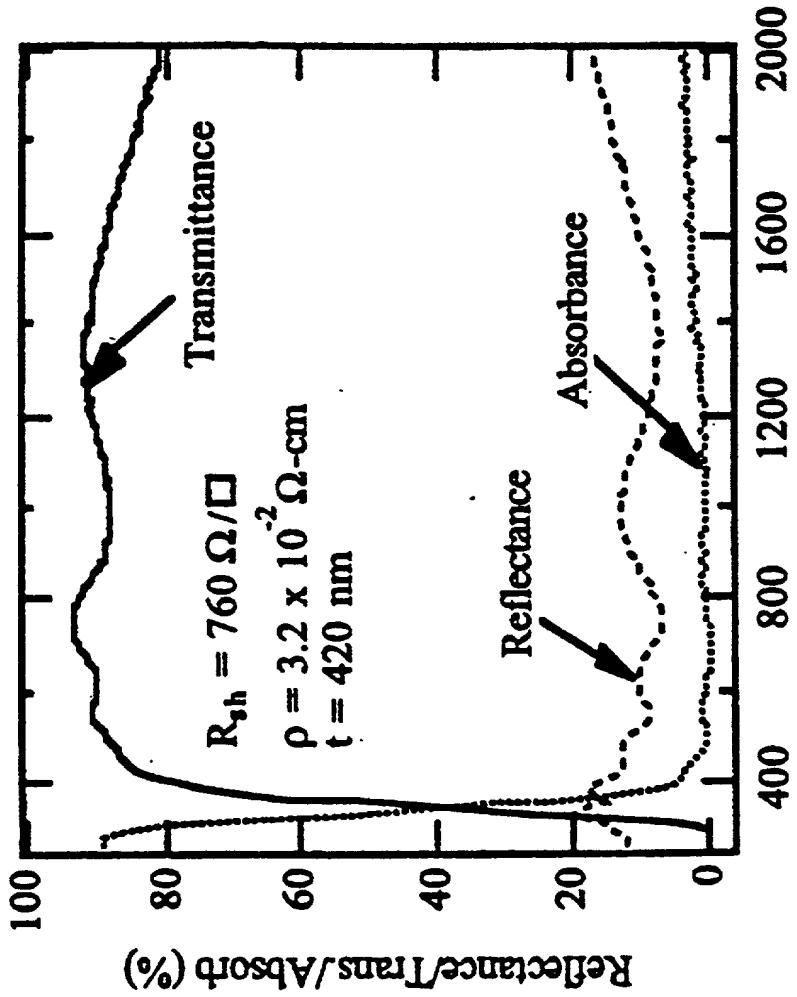


Transmission Spectra for Zinc Stannate Films Deposited with Oxygen Partial Pressures of 0 Pa [curve (a)], Film Thickness of 470nm], 2 mPa [curve (b), 310 nm] and 5 mPa [curve (c), 300 nm].

(From T. Minami et al, Properties of Transparent Zinc-Stannate Conducting Films, JVSTA, 13, 3 1995)

## ADVANCED TOPICS

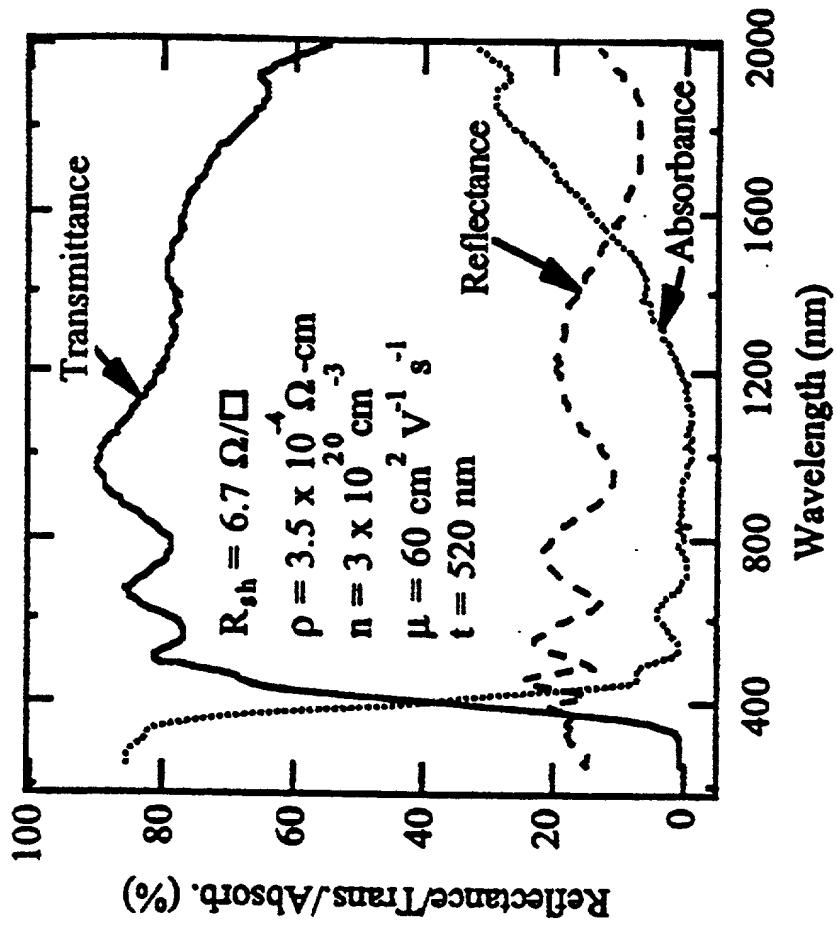
### NEW TCO MATERIALS



Transmittance, Reflectance, and Absorbance for a  $\text{Zn}_2\text{SnO}_4$  Film.  
(From X. Wu et al, Properties of Transparent Conducting  $\text{Cd}_2\text{SnO}_4$  and  $\text{Zn}_2\text{SnO}_4$ , 3<sup>rd</sup> SVC, 1996)

## ADVANCED TOPICS

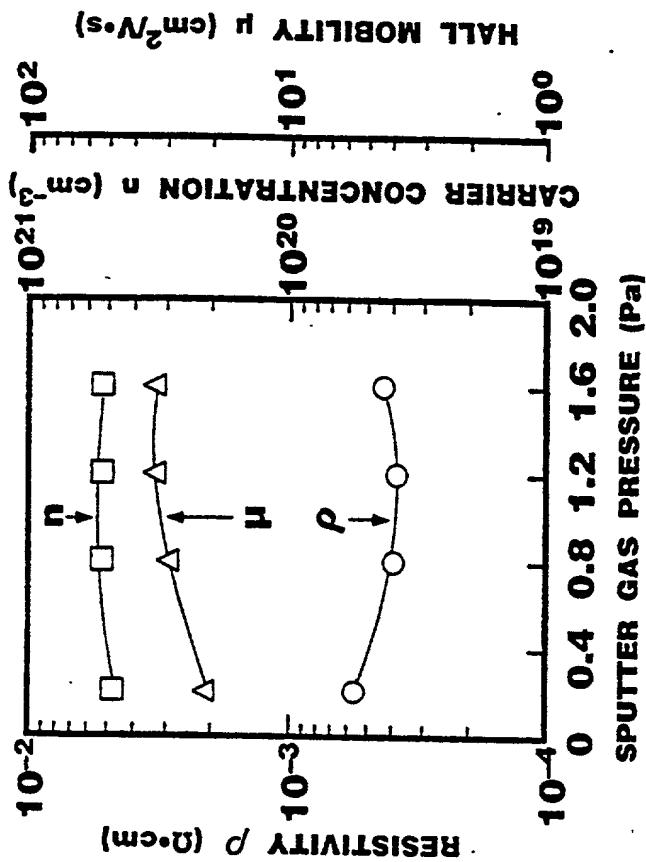
### NEW TCO MATERIALS



Transmittance, Reflectance, and Absorbance for a  $\text{Cd}_2\text{SnO}_4$  Film.  
(From X. Wu et al, Properties of Transparent Conducting  $\text{Cd}_2\text{SnO}_4$  and  $\text{Zn}_2\text{SnO}_4$ , 3<sup>rd</sup> SVC, 1996)

## ADVANCED TOPICS

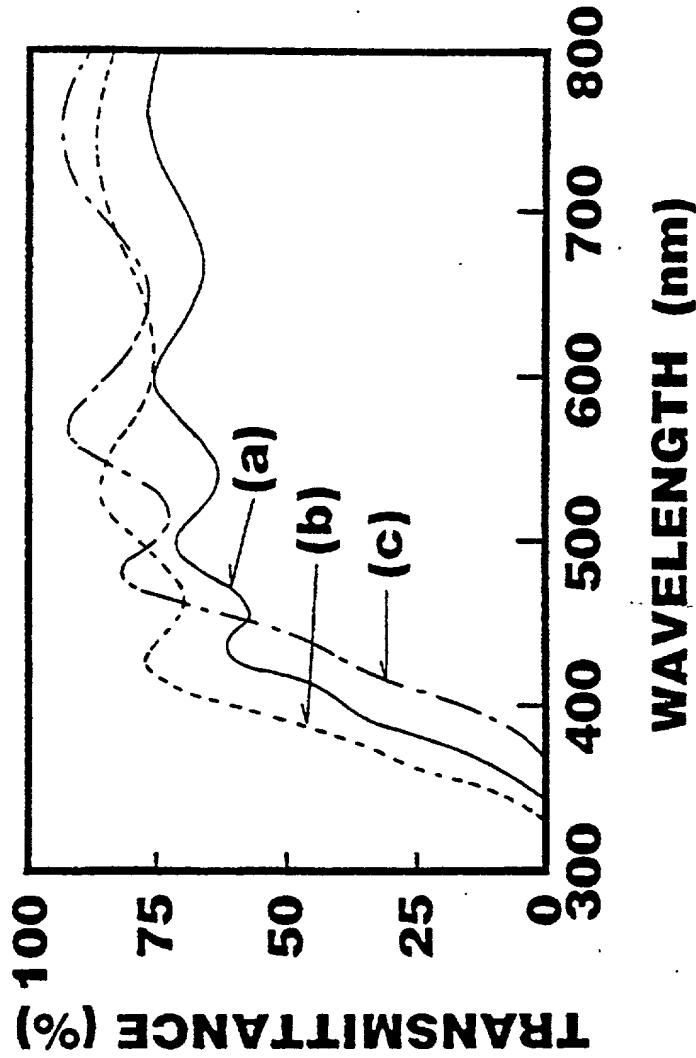
### NEW TCO MATERIALS



**Resistivity (o), Carrier Concentration (□) and Hall Mobility ( $\Delta$ ) as a Function of Sputter Gas Pressure for  $\text{Zn}_2\text{In}_2\text{O}_5$  Films (Substrate  $\sim 140^\circ\text{C}$ ).**  
(From T. Minami et al, New Transparent Conducting  $\text{Zn}_2\text{In}_2\text{O}_5$  Thin Films, ICMCTF, 1995)

## **ADVANCED TOPICS**

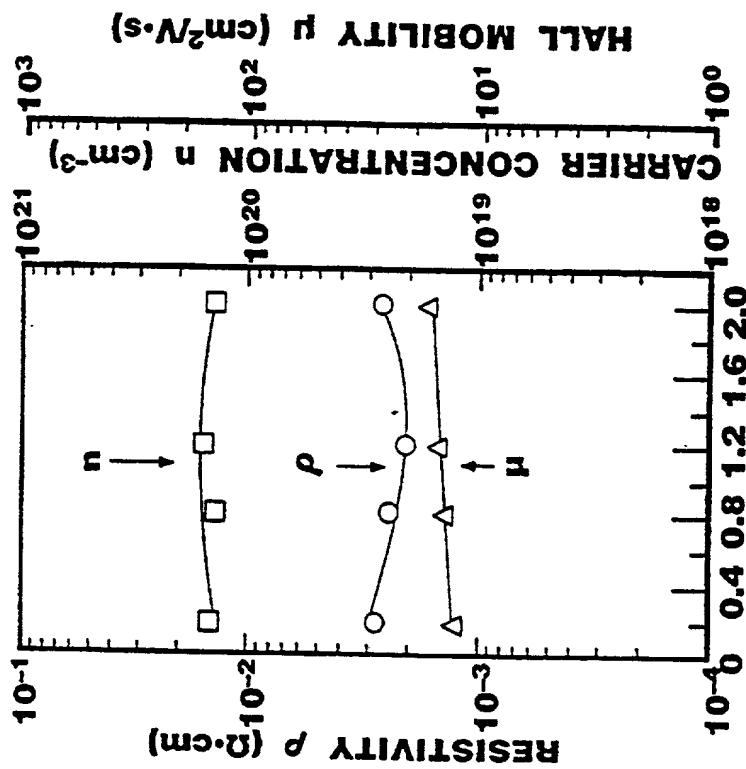
### **NEW TCO MATERIALS**



**Optical Transmission for  $Zn_2In_2O_5$  Films Prepared with Different Conditions;** (a) RT Substrate ( $\sim 140^{\circ}C$ ), Ar only, (b)  $350^{\circ}C$  Substrate, Ar only, (c) RT Substrate ( $\sim 140^{\circ}C$ ), Ar 20% +  $O_2$ .  
(From T. Minami et al, New Transparent Conducting  $Zn_2In_2O_5$  Thin Films, ICMCTF, 1995)

## ADVANCED TOPICS

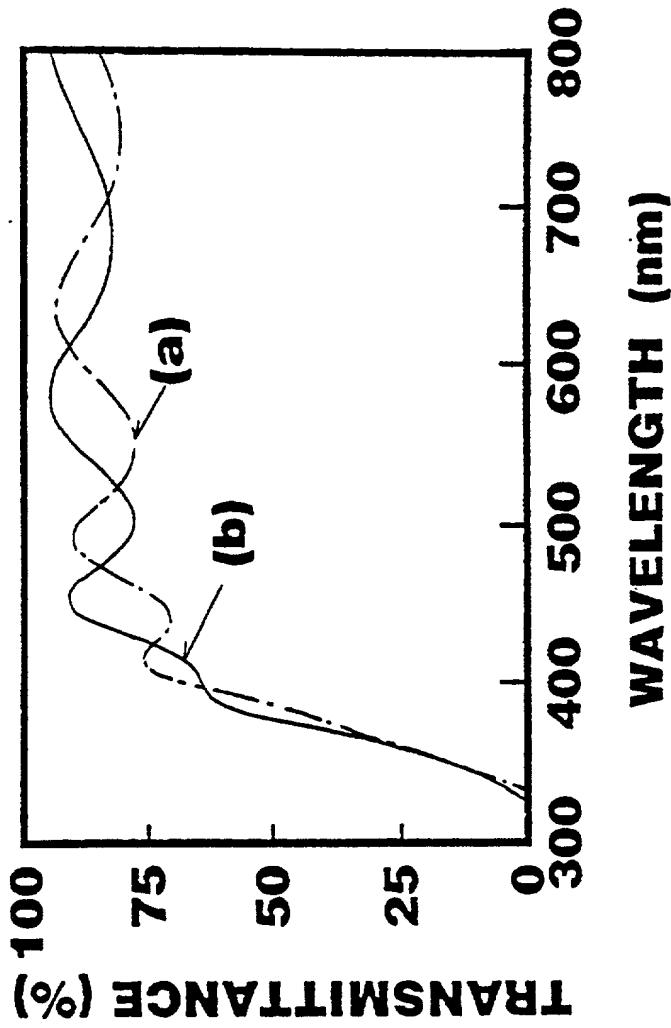
### NEW TCO MATERIALS



**Resistivity (○), Carrier Concentration (□) and Hall Mobility (△) as a Function of Sputter Gas Pressure for  $\text{MgIn}_2\text{O}_4$  Films (RT Substrate  $\sim 140^\circ\text{C}$ ).**  
(From T. Minami et al, New Transparent Conducting  $\text{Zn}_2\text{In}_2\text{O}_5$  Thin Films, ICMCTF, 1995)

## **ADVANCED TOPICS**

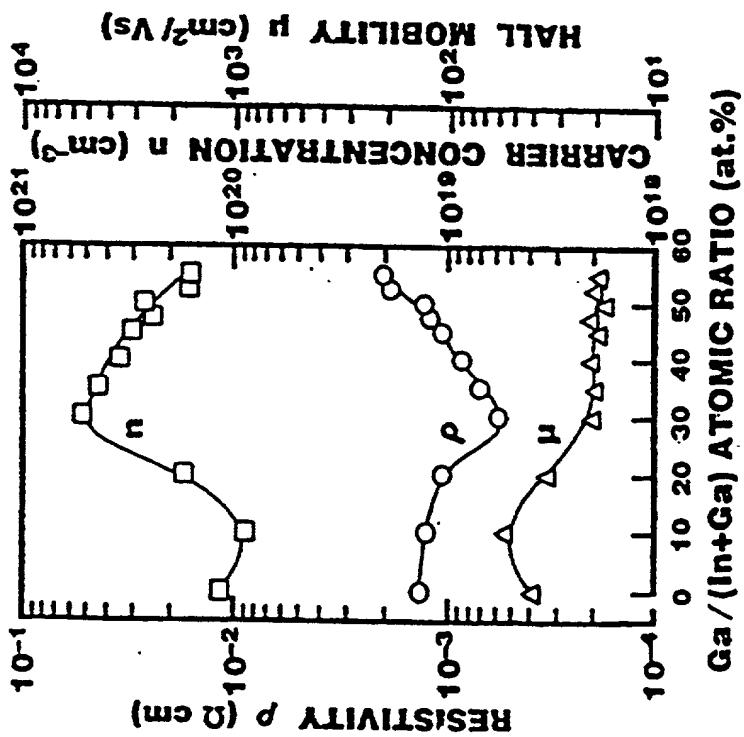
### **NEW TCO MATERIALS**



**Optical Transmission of  $MgIn_2O_4$  Films [Ar pressure (a) 0.8 Pa, (b) 1.2 Pa].**  
(From T. Minami et al, New Transparent Conducting  $MgIn_2O_4$  Thin Films, ICMCTF, 1995)

## ADVANCED TOPICS

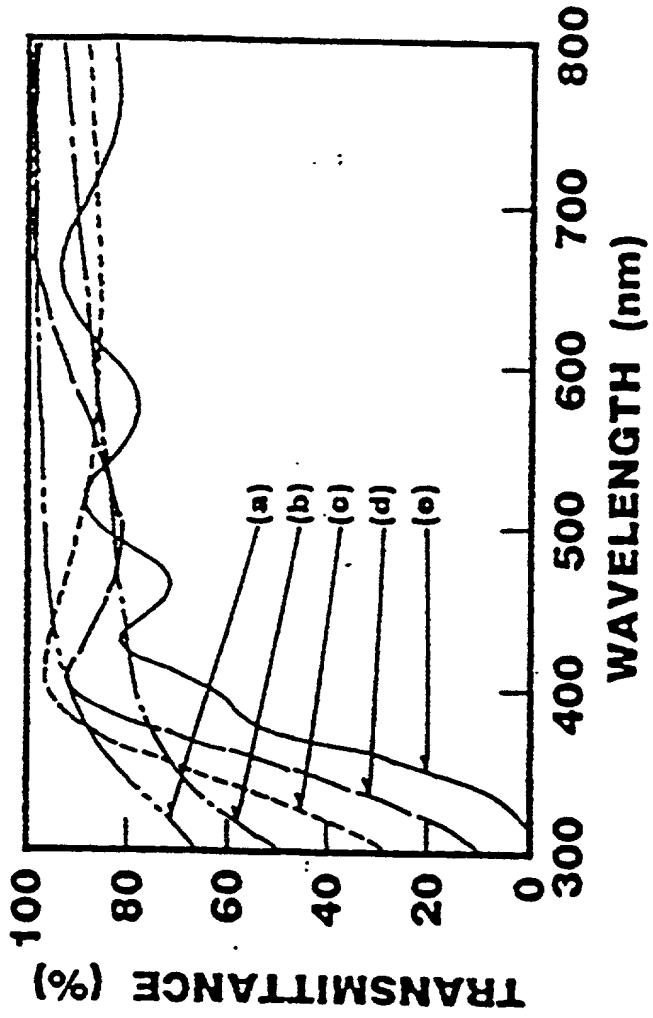
### NEW TCO MATERIALS



**Resistivity (o), Carrier Concentration (□) and Hall Mobility ( $\Delta$ ) as Functions of Ga Content for  $\text{Ga}_2\text{O}_3\text{-In}_2\text{O}_3$  Films Prepared at RT ( $\sim 180^\circ\text{C}$ ).**  
(From T. Minami et al, Preparation of Highly Transparent Films, JVST A, 15, 3 1997)

## ADVANCED TOPICS

### NEW TCO MATERIALS



Transmittance of  $(\text{Ga}, \text{In})_2\text{O}_3$  Films Prepared at RT ( $\sim 180^\circ\text{C}$ ) With Ga Content of 50 at. % and Thickness of (a) 20, (b) 55, (c) 100, (d) 185 and (e) 500 nm.  
(From T. Minami et al, Preparation of Highly Transparent Films, JVST A, 15, 3 1997)

## ADVANCED TOPICS

### EXCIMER LASER (XeCl @ 308 nm) ABLATION

- ELECTRICAL AND OPTICAL PROPERTIES OF ZnO FILMS PREPARED AT SUBSTRATE TEMPERATURE OF 300°C.

	Al-doped ZnO	Ga-doped ZnO
Resistivity ( $\Omega \cdot \text{cm}$ )	$1.4 \times 10^{-4}$	$2.7 \times 10^{-4}$
Hall mobility ( $\text{cm}^2/\text{V} \cdot \text{s}$ )	45	18
Carrier concentration ( $\text{cm}^{-3}$ )	$9.9 \times 10^{20}$	$1.3 \times 10^{21}$
Transmittance (%)	90	90
Film thickness (nm)	150	230
Dopant in target (wt%)	1.0	7.0

(From K Imaede et al, Highly Conductive and Transparent ZnO :Al Thin Films, Presented at 43<sup>rd</sup> AVS, 1996)

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SECTION I: FUNDAMENTALS OF CONDUCTIVITY AND THIN FILM OPTICS

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  4. O.S. Heavens, *Optical Properties of Thin Solid Films*, Dover Publications, New York, 1965
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  7. K.L. Chopra, S. Major and K. Pandya, "Transparent conductors - a status review", *Thin Solid Films*, 102, 1-46 (1983)
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## SECTION II: TCC FUNCTION AND PERFORMANCE IN APPLICATIONS

1. C.M. Lampert, "Heat mirror coatings for energy conserving windows". *Solar Energy Mat.* **6**, 1 (1981)
  2. J.C.C. Fan, "Sputter films for wavelength-selective applications". *Thin Solid Films*, **80**, 125 1981

### **SECTION III: MAJOR DEPOSITION METHODS FOR TCC**

## SECTION V: DEVELOPING A TCO DEPOSITION PROCESS

## SECTION IV: IMPORTANT PROCESS PARAMETER FOR TRANSPARENT CONDUCTIVE OXIDES (TCO)

## SECTION V: DEVELOPING A TCO DEPOSITION PROCESS

## **SECTION VI: TWO PROCESS EXAMPLES AND ASSOCIATED COATING PROPERTIES**

1. D.B. Fraser and H.D. Cook, "Highly conductive transparent films of sputtered  $\text{In}_{2-x}\text{Sn}_x\text{O}_3$ ," J. Electrochem. Soc., 119, 1368 (1972).

## REFERENCES PART II

### SECTION VII: STRATEGY FOR DEVELOPING A TCC TO MEET SPECIFIC APPLICATION REQUIREMENTS

### SECTION VIII: APPLICATION EXAMPLES

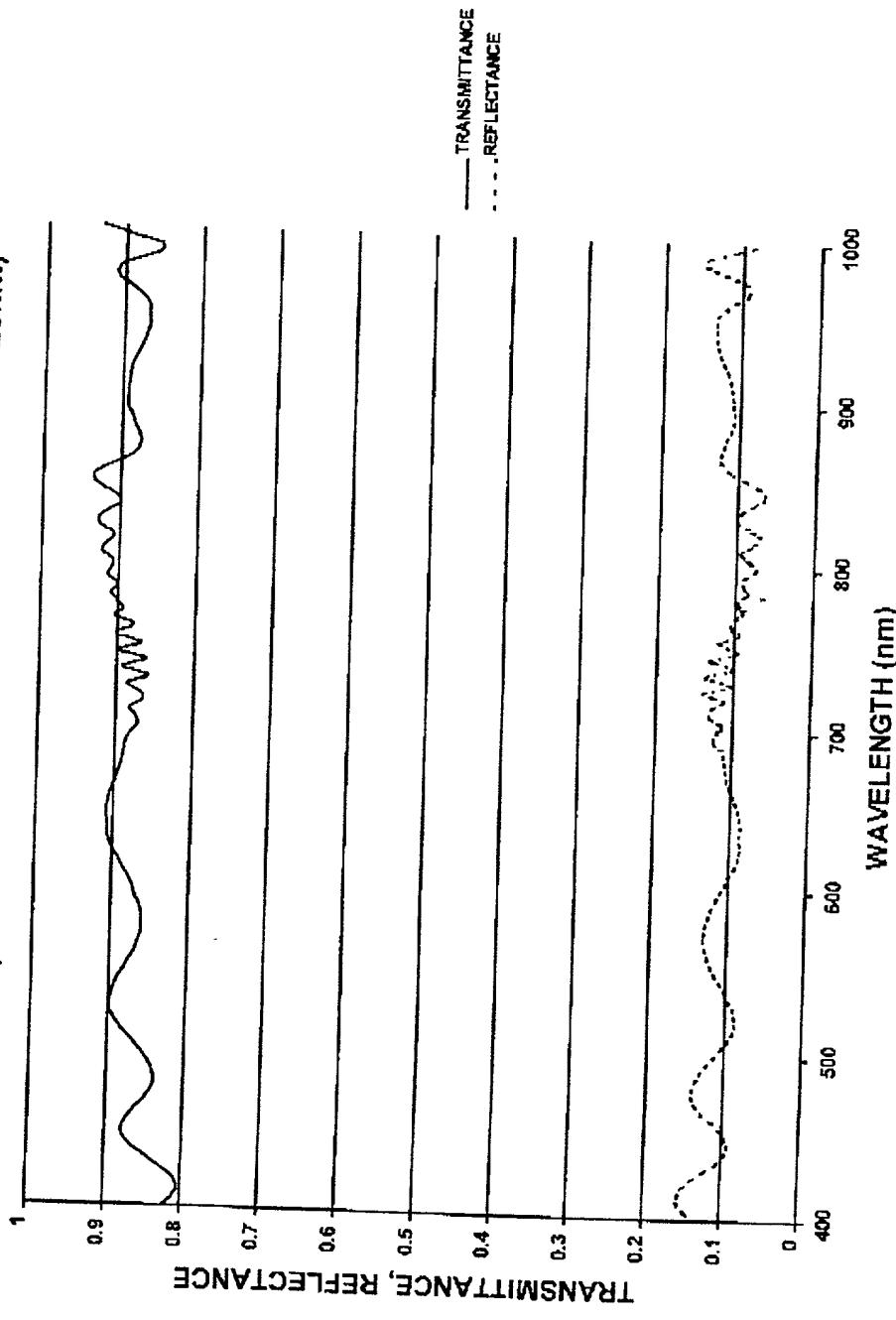
### SECTION IX: SPECIFYING AND SELECTING COMMERCIALLY AVAILABLE TCC

### SECTION X: ADVANCED TOPICS

1. T. Minami, Y. Takeda, T. Kakuma, S. Takata and I. Fukuda, "Preparation of highly transparent and conducting  $Ga_2O_3 - In_2O_3$  films by DC magnetron sputtering", J. Vac. Sci. Technol. A 15(3) May/Jun 1997
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3. X. Wu, W.P. Mulligan and T.J. Coutts, "Electrical and Optical properties of transparent conducting cadmium stannate and zinc stannate thin films prepared by RF sputtering", in Proc. of 39<sup>th</sup> Annual Technical Conference, Society of Vacuum Coaters", 1996
4. T. Minami, S. Takata, T. Kakuma, and H. Sonohara, "New transparent conducting  $MgIn_2O_4 - Zn_2In_2O_5$  thin films prepared by magnetron sputtering", Proc. Of ICMCTF, (1995)
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# TRANSPARENT BARRIER COATINGS BASED ON ITO FOR FLEXIBLE PLASTIC DISPLAYS

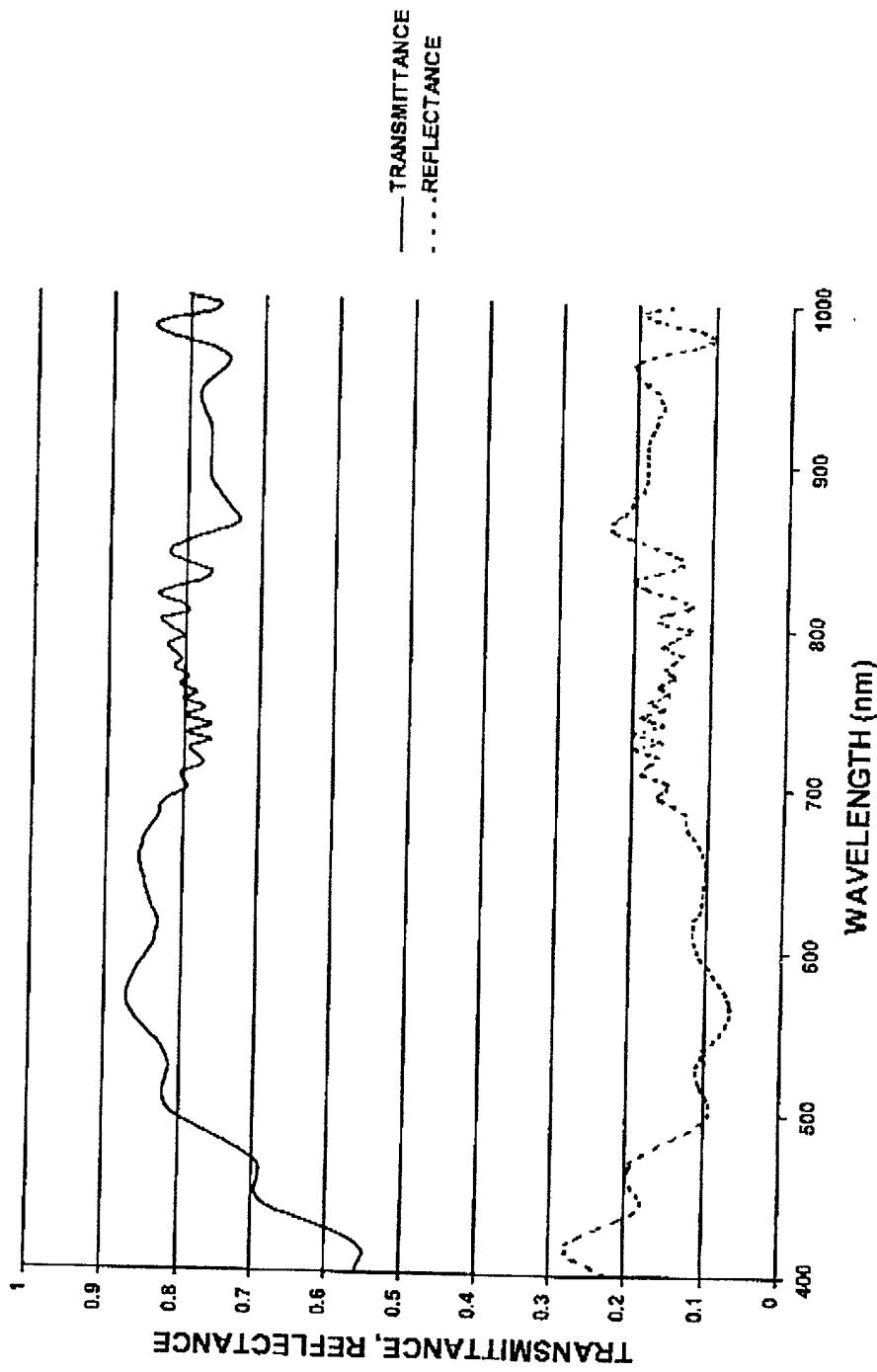
TRANSMITTANCE AND REFLECTANCE OF SEMI-REACTIVELY  
SPUTTERED ITO ON PET (POLYMER/ITO= 25nm)



Appendix  $\Pi$

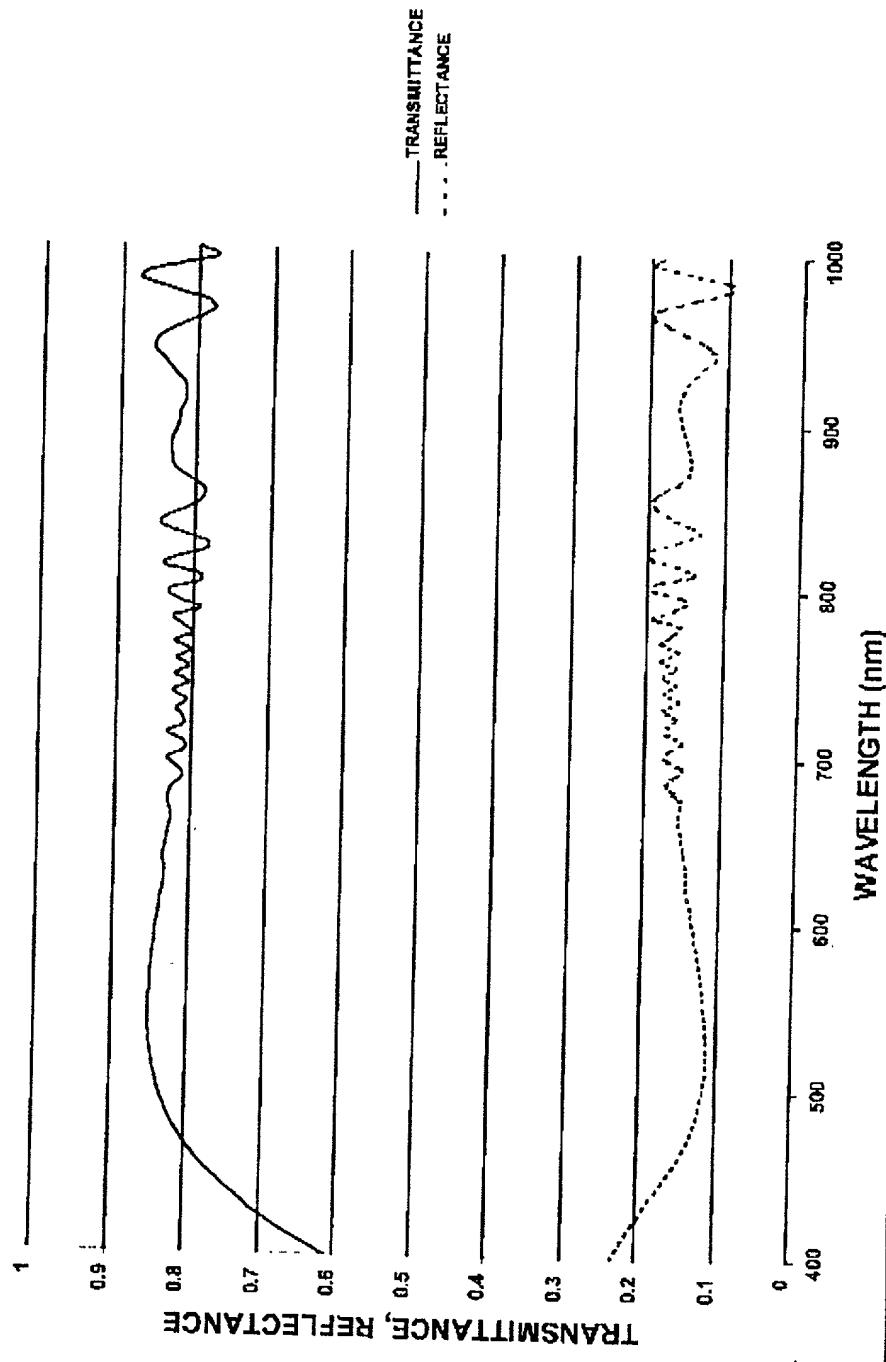
# TRANSPARENT BARRIER COATINGS BASED ON ITO FOR FLEXIBLE RASTIC DISPLAYS

TRANSMITTANCE AND REFLECTANCE OF SEMI-REACTIVELY  
SPUTTERED ITO ON PET (POLYMER/ITO= 153 nm)



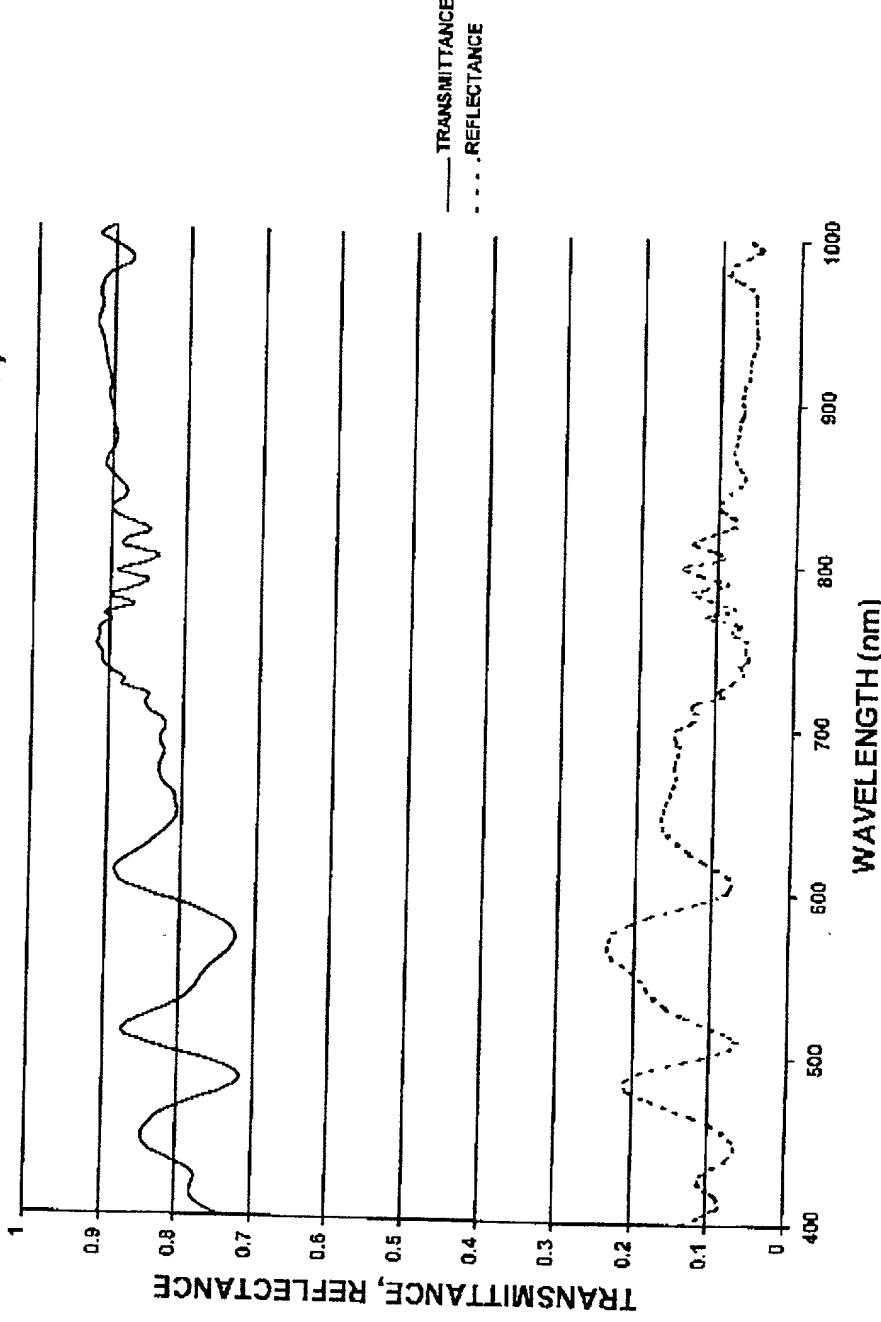
# TRANSPARENT BARRIER COATINGS BASED ON ITO FOR FLEXIBLE PLASTIC DISPLAYS

TRANSMITTANCE AND REFLECTANCE OF SEMI-REACTIVELY  
SPUTTERED ITO ON PET (SINGLE LAYER ITO 134 nm)



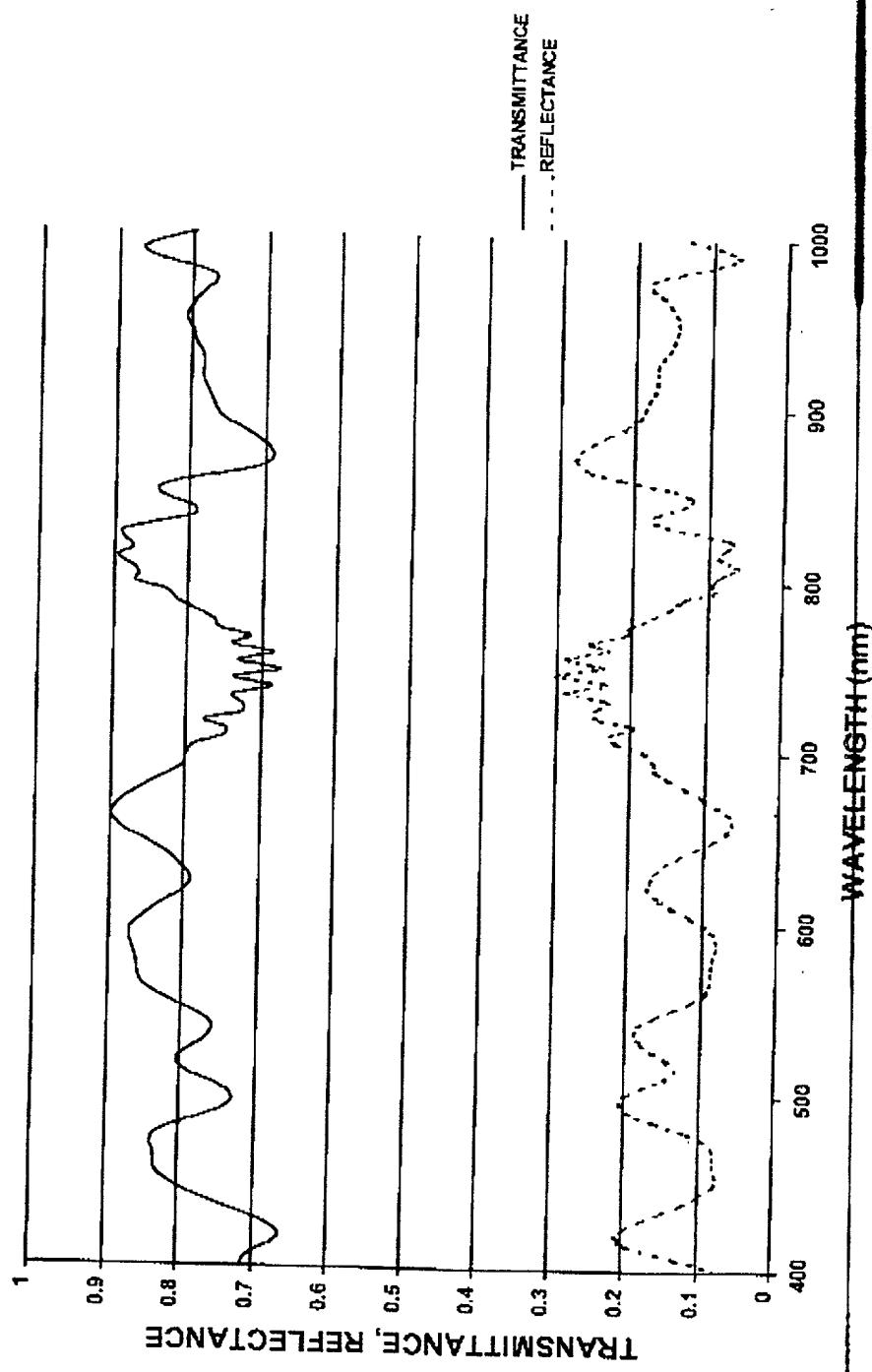
# TRANSPARENT BARRIER COATINGS BASED ON ITO FOR FLEXIBLE PLASTIC DISPLAYS

TRANSMITTANCE AND REFLECTANCE OF SEMI-REACTIVELY  
SPUTTERED ITO/POLYMER ON PET  
(TWO ITO LAYERS = 50nm TOTAL)



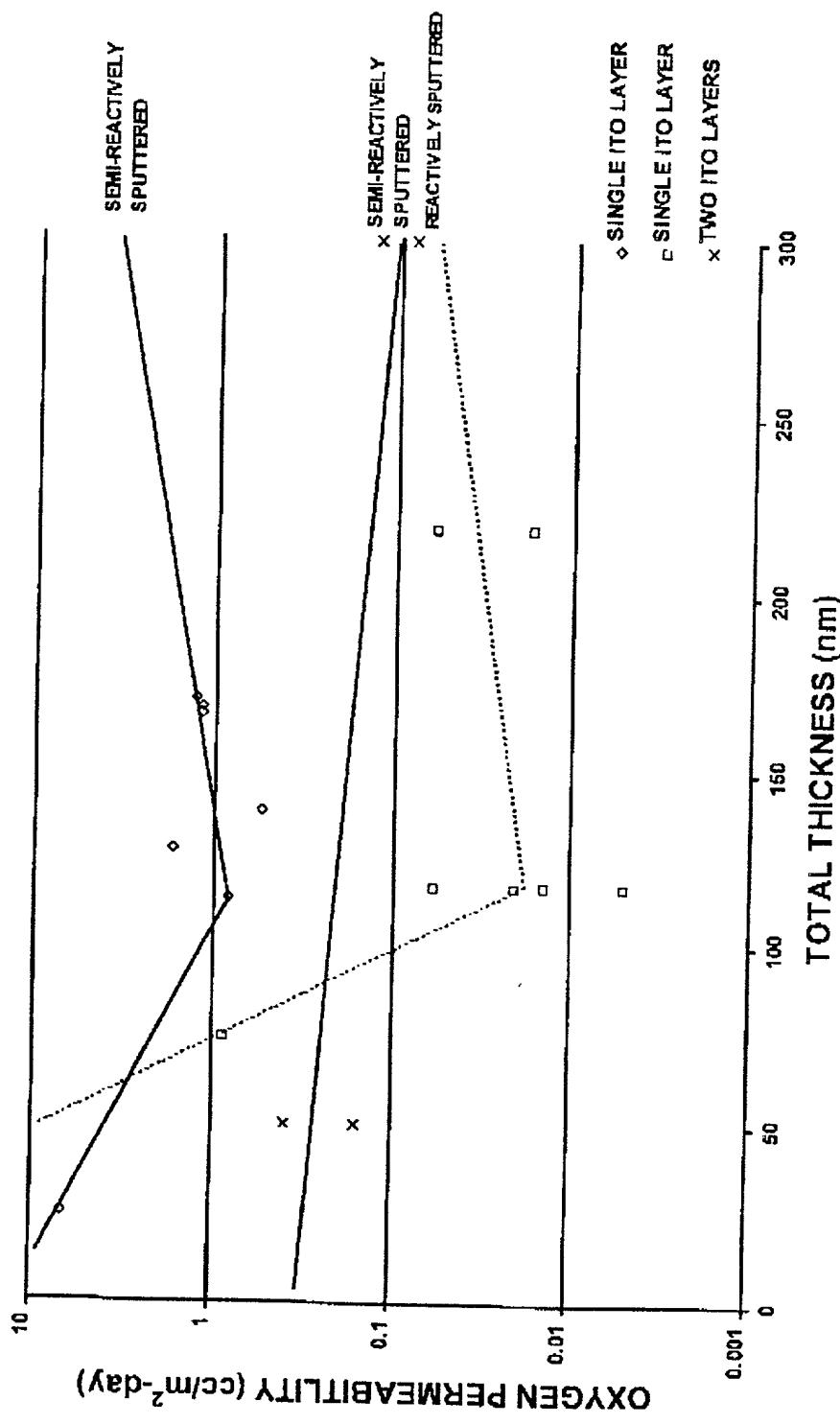
# TRANSPARENT BARRIER COATINGS BASED ON ITO FOR FLEXIBLE PLASTIC DISPLAYS

TRANSMITTANCE AND REFLECTANCE OF  
SEMI-REACTIVELY SPUTTERED ITO POLYMER ON PET  
(TWO ITO LAYERS = 299nm TOTAL)



# TRANSPARENT BARRIER COATINGS BASED ON ITO FOR FLEXIBLE PLASTIC DISPLAYS

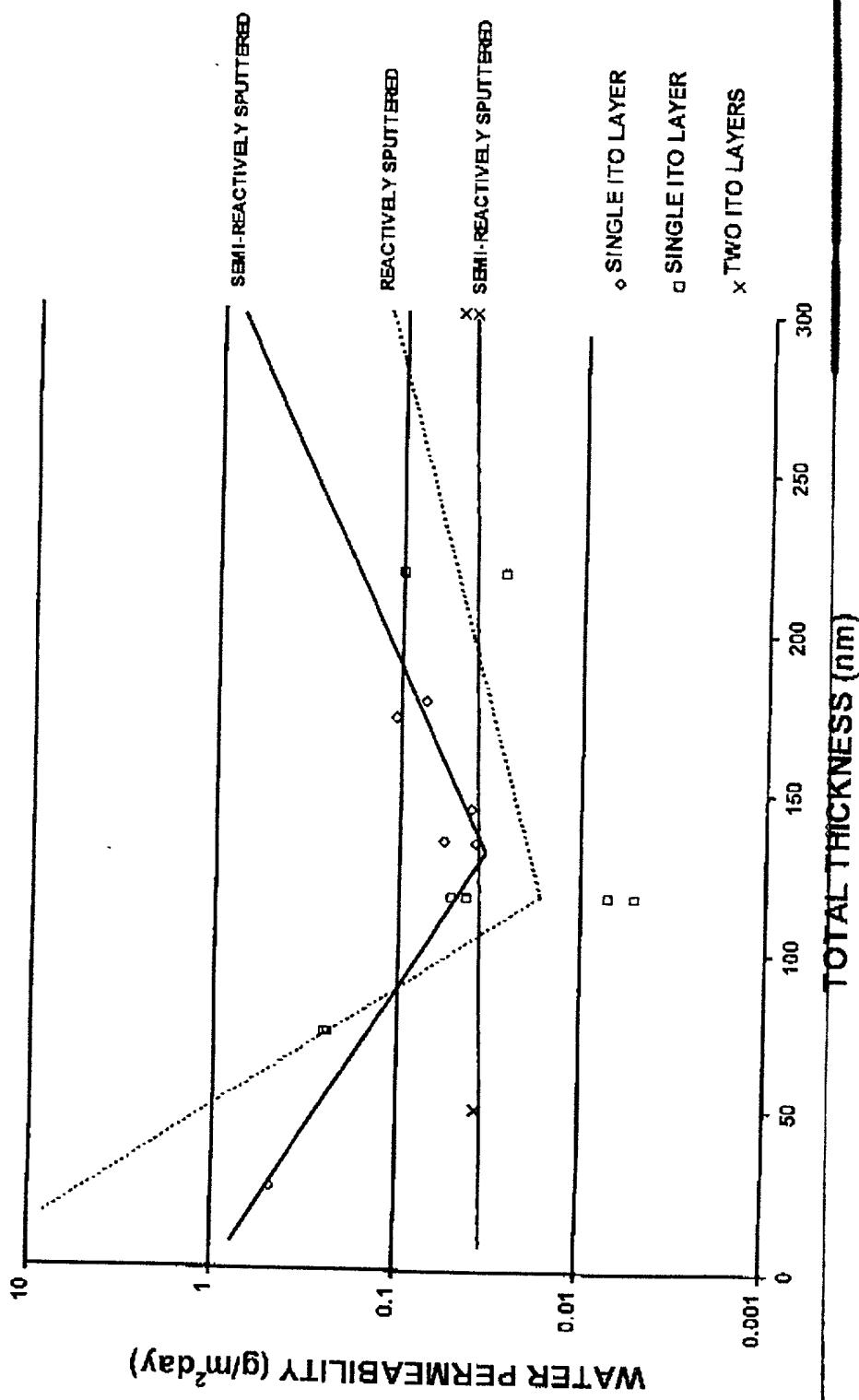
## OXYGEN PERMEABILITY VERSUS ITO THICKNESS



Appendix D

# TRANSPARENT BARRIER COATINGS BASED ON ITO FOR FLEXIBLE PLASTIC DISPLAYS

## WATER VAPORPERMEABILITY VERSUS ITO THICKNESS



# TRANSPARENT BARRIER COATINGS BASED ON ITO FOR FLEXIBLE PLASTIC DISPLAYS

## Experimental Results For ITO Barriers on PET

### Semi-Reactively Sputtered

Total ITO Thickness (nm)	Surface Resistivity (ohms/square)	Rho ( $\times 10^{-4}$ n-cm)	Luminoust (%)	H <sub>2</sub> O Permeance (cc/m <sup>2</sup> -day)	O <sub>2</sub> Permeance (g/m <sup>2</sup> -day)
123.3	38.3	4.685	84	0.038	0.827
172.4	29.9	5.145	82	0.073	1.19
299.2	17.2	5.15	~81	0.049	0.081
49.9	188.4	9.4	~81	0.036	0.156

# TRANSPARENT BARRIER COATINGS BASED ON ITO FOR FLEXIBLE PLASTIC DISPLAYS

## Experimental Results For ITO Barriers on PET

### Semi-Reactively Sputtered

Total ITO Thickness (nm)	Surface Resistivity (ohms/square)	Rho ( $\times 10^{-4}$ n-cm)	Luminoust (%)	H <sub>2</sub> O Permeance (cc/m <sup>2</sup> -day)	O <sub>2</sub> Permeance (g/m <sup>2</sup> -day)
218.5	31.8	6.94	~80	0.0621	0.038
117.05	57.48	6.64	~82	0.12	0.0246
74.3	348.5	25.6	~86	0.2375	0.8625